INVESTIGATION OF AN
ELECTRIC GOVENOR DESIGN

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by

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PREFACE

This thesis subject was suggested by Mr. T. P. Kirkpatrick of the U. S. Naval Engineering Experiment Station. The governor system referred to in this thesis is one being developed for the Navy Department, Bureau of Ships by Industrial Research Laboratories of Baltimore.

Many difficulties had arisen in the adaption of the system design for use with a magnetic amplifier and progress had slowed almost to a standstill for the past year. Consequently Mr. Kirkpatrick considered it worthwhile that an attempt be made to analyze the system from a fresh viewpoint, in hope that new information might be obtained which would lead to an early conclusion of the project.

It is wished to specifically acknowledge the assistance given by Mr. G. P. Stout, director of I.R.L., in allowing me to work on this project, as well as that by Mr. H. J. Chyba and Mr. R. T. Towner of I.R.L., for allowing me to work along with them, and by Professor C.V.O. Terwilliger and Associate Professor W. C. Smith of the Postgraduate School, and to thank collectively the other members of the Electrical Engineering Department of the Postgraduate School for their individual help and counsel.

This work was performed between January and June 1950 at the U. S. Naval Engineering Experiment Station, Annapolis, Md.

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CHAPTER I

INTRODUCTION

The system under investigation was designed to fulfill the need for a fast responding governor for shipboard prime movers driving 60 cycle a-c generators which in normal operation will be required to pick up or drop loads approaching full capacity with a minimum frequency deviation. The system was designed by Industrial Research Laboratories under Navy contract NObs 47126 to meet the following specifications: (1) line frequency deviation under steady load conditions, 0.15 cycles/sec. (1/4%); (2) line frequency deviation under application or removal of full load, 2.4 cycles/sec. (4%) for a period not exceeding one half second; and (3) line frequency deviation during recovery period following the one half second period, 0.3 cycles/sec. (1/2%).

The basic governor system consists of a simple closed loop servo system composed of a frequency detector yielding a frequency error signal which is fed to an amplifier driving a servo motor which controls the fuel input of the prime mover and hence its output. Frequency is taken from the output of the a-c generator and fed back to the frequency detector, thus closing the primary loop of the servo system. Such a system would theoretically (and actually) control the output frequency of the a-c generator but its speed of response would be on the same order as that of a mechanical governor. This is due to the fact that the prime mover-generator set contains appreciable inertia, both mechanical (in both prime mover and generator) and electrical (in the generator) which means there will be an appreciable time lag before the generator, under application of a stepwise load change, changes speed sufficiently to

to generate the minimum or threshold signal at the input of the amplifier. Beyond this point in time, the generator speed deviation is increasing and the error signal through the amplifier increases until enough control is exerted on the prime mover to bring the system back to normal speed and frequency. Thus after application of a load change, the prime mover control "sees" a dead period of time followed by a period when an insufficient but increasing amount of control is applied. To overcome this inescapable sluggishness of the system, it would be desirable to inject a large signal as soon as the load change occurs, a signal which would then decrease and die out as the frequency error signal takes over. Such an anticipatory circuit is included by the incorporation of a load change detector which sends a signal proportional to the derivative of the change in load current to the amplifier.

It will be noted that so far no mention has been made of any time delays in the governor system proper. Due to such time constants with their combined tendency to make the system unstable, plus such practical considerations as the tendency of the servo motor (a two phase a-c motor) to overshoot upon removal of signal to the control phase, it was found necessary to include a third (stabilizing) feedback loop which would send a signal to the amplifier proportional to the position of the control motor (and hence of control setting of the prime mover). Figure 1 is a block diagram of the system.

The first stage of development of the governor consisted of the design of the above component circuits and their assembly into a governor system using an electronic amplifier. It was felt that the use of an electronic amplifier would simplify initial design since its time constant is negligible compared to the other circuits in the system,

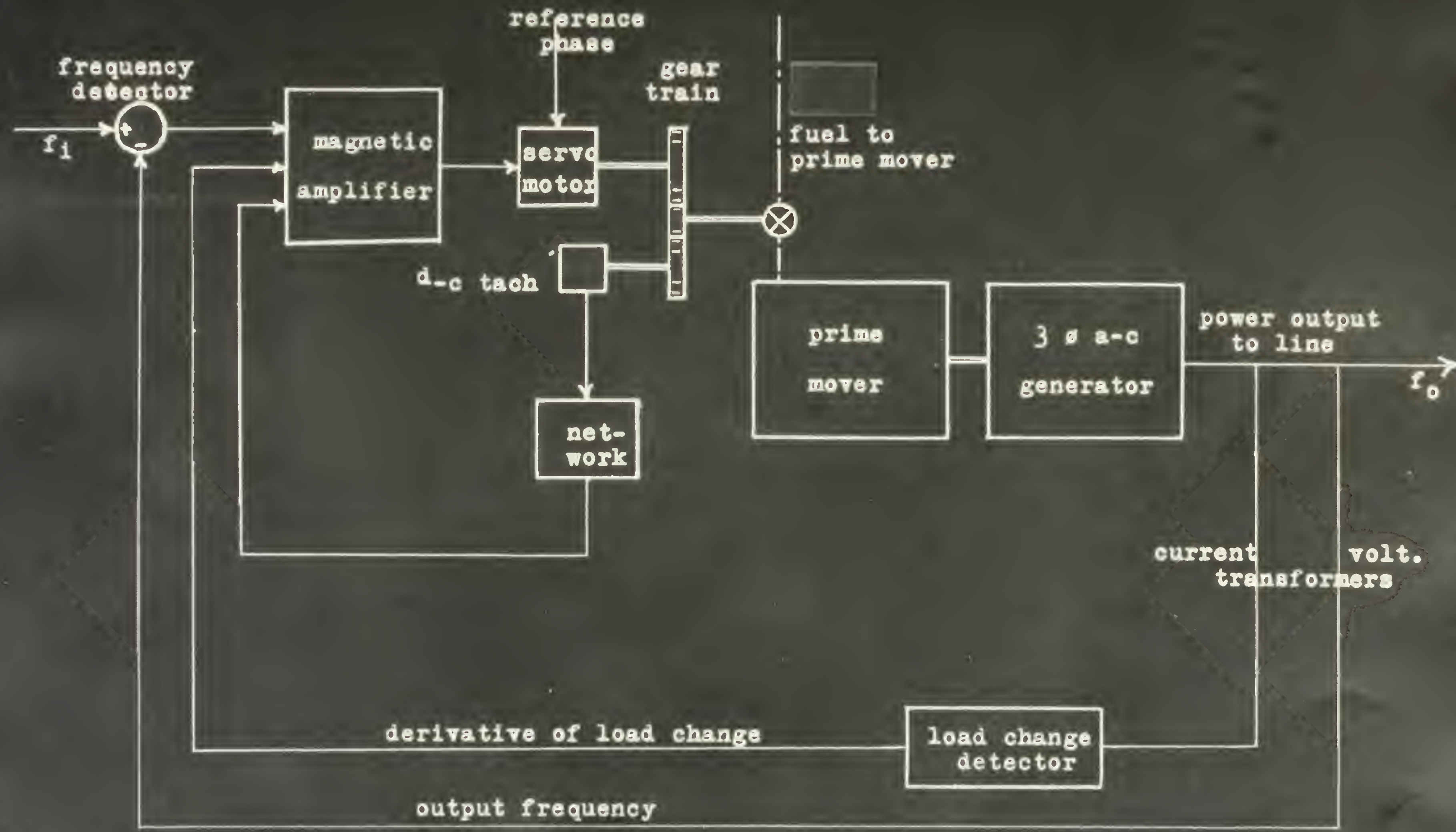

frequency detector
f_i
reference phase
magnetic amplifier
servo motor
gear train
fuel to prime mover
d-c tach
net-work
prime mover
3 ø a-c generator
power output to line
f_o
current
volt.
transformers
derivative of load change
load change detector
output frequency

Figure 1.

plus the fact that its input is, for all practical purposes, purely resistive.

The frequency detector, figure 2, is essentially a tuned bridge rectifier which supplies direct current proportional in polarity and magnitude to the frequency deviation from 60 cycles. Figure 3 shows the response characteristic of the frequency detector operating into a 5000 ohm load.

The load change detector, figure 4, is a rectifier filter combination which converts a-c load current to direct current, followed by an RC network to give an (approximate) derivative of load current change.

For the stabilizing feedback circuit the simplest way of obtaining a direct current proportional to control (throttle) position would be from a potentiometer driven by the gear train between servo motor and throttle, said potentiometer being placed across a constant d-c source. However, contract specifications forbade the use of any moving contacts and when it was found that a variable d-c could not practically be produced at this point without moving contacts, the use of a d-c tachometer, Electric Indicator Co., Model FBZ 193 (approved JAN specifications) was allowed. The use of a tachometer required an RC network to give an (approximate) integral of throttle rate of change of position, i.e., throttle or servo motor position. Figure 5 shows this stabilizing circuit.

The outputs of the frequency detector, load change detector and stabilizing circuit (or tach loop as it will be called hereafter) were connected in series to the input of the electronic amplifier. A Diehl model FPE 49-7, 10 watt, 115 volt, 60 cycle, two phase a-c motor was used as the servo motor.

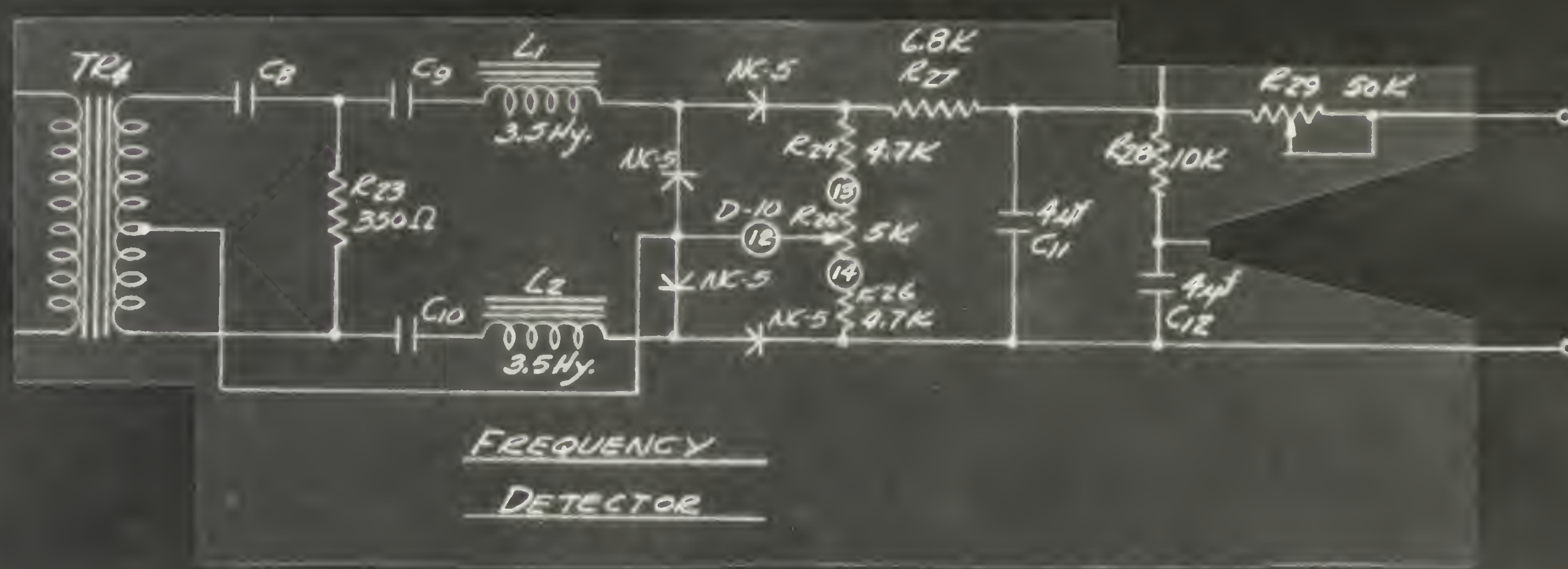


Figure 2.

Courtesy of Industrial Research Laboratorie

OUTPUT OF FREQUENCY DETECTOR

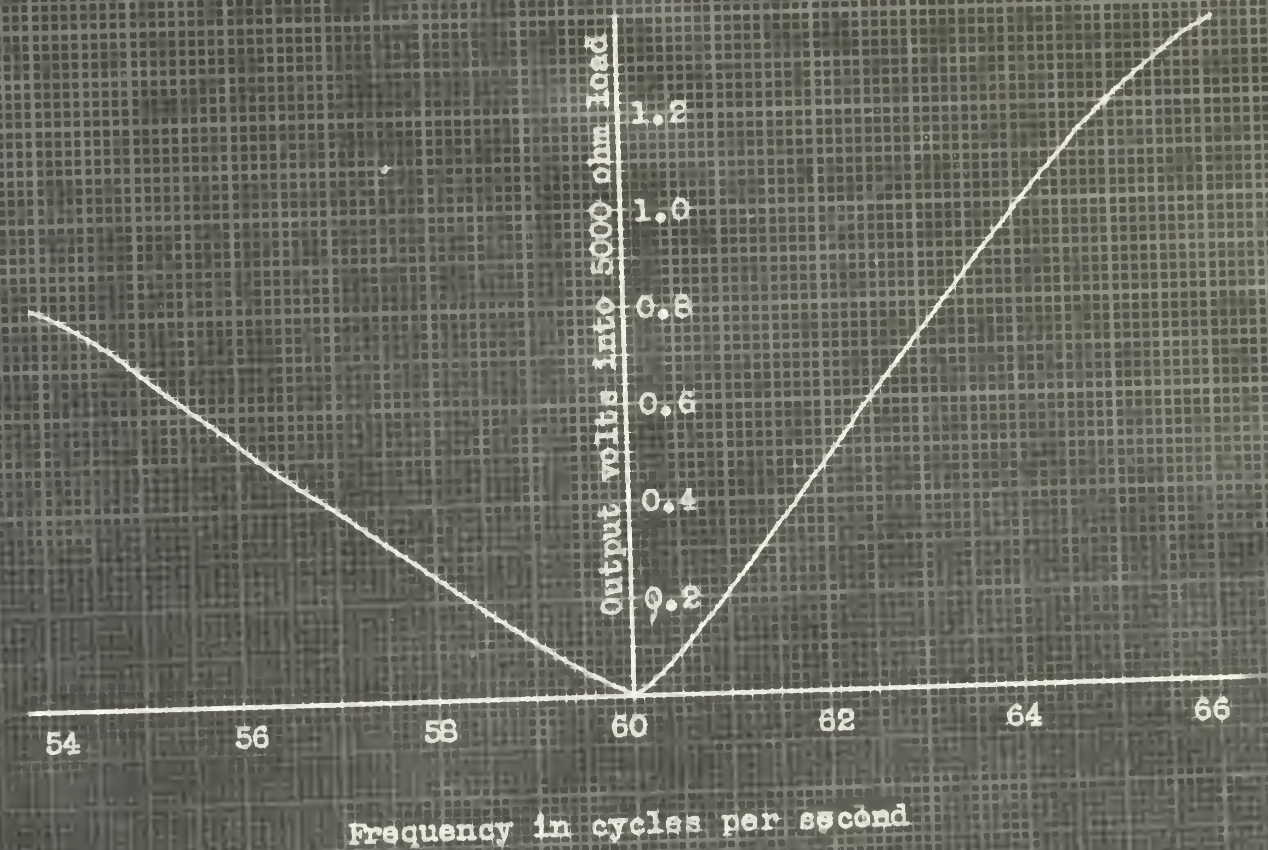


Figure 3.

TACHOMETER PLUS INTEGRAL NETWORK

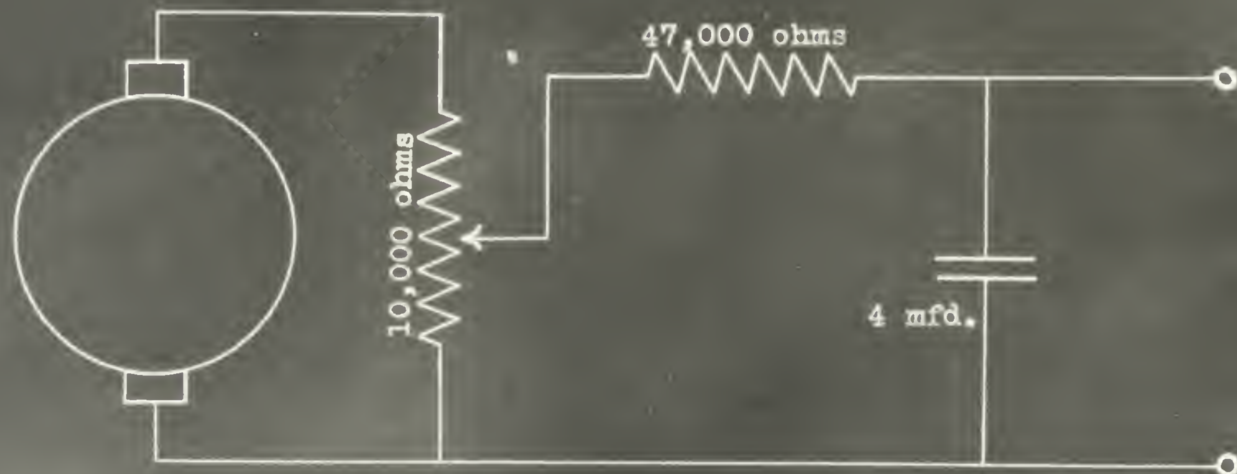


Figure 15.

Courtesy of Industrial Research Laboratories

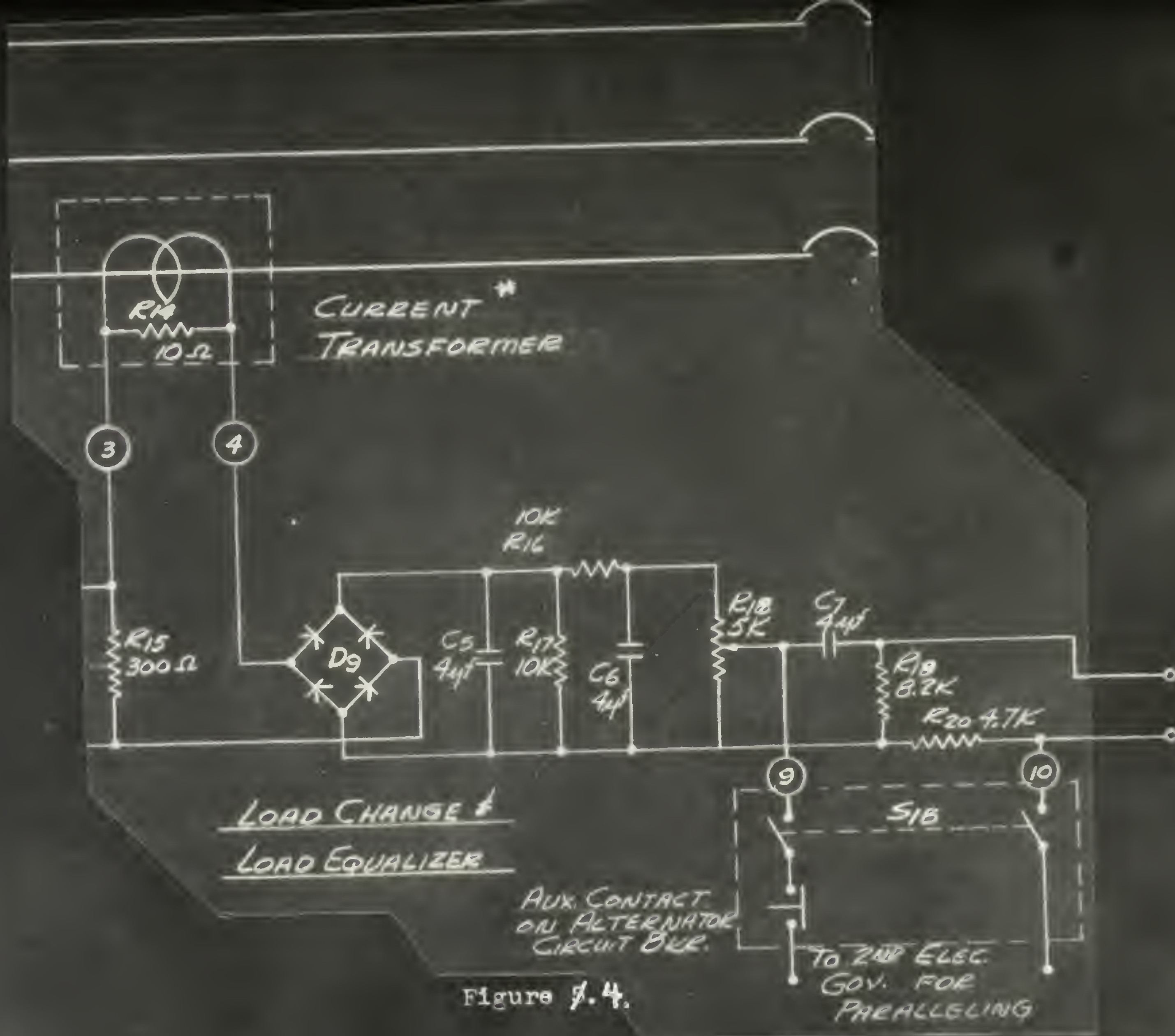


Figure 1.4.

Courtesy of Industrial Research Laboratories

A 40 kilowatt GM direct coupled diesel generator set was supplied by the U. S. Naval Engineering Experiment Station for testing and adjustment of this system. Figure 6 is a record of the best operation of this system, which will be seen to fall within contract specifications.

The final design as desired by the Navy could contain no vacuum tubes since a rugged, dependable unit was desired which would not require constant maintenance by electronic technicians and which could be placed back in the engineering spaces.

Thus the second stage of development took place which consisted of replacing the electronic amplifier by a magnetic amplifier and modifications of the circuits necessitated by this change.

A magnetic amplifier was supplied by the Ward Leonard Co., built to Industrial Research Laboratories' specifications. These specifications covered a 60 cycle, 450 volt amplifier with a 10 watt output at 115 volts. It was to have three 5000 ohm control windings and a fairly short time constant (otherwise unspecified). It should give full output for inputs of approximately 1 volt on all input windings. As designed the amplifier is a two stage unit, the first stage being separately biased and containing a feedback winding. The second stage is self biased and derives its control from the rectified output of the first stage. Part of the output is rectified and may be used as feedback to the first stage. Figure 7 is a diagram of the amplifier.

The magnetic amplifier was substituted in the system and the governor placed in operation. The system was completely unstable, as evidenced by hunting of the servo motor and throttle through the full throw of the fuel rack. Outputs of the three control loops to the amplifier were varied in magnitude to no avail. The amplifier feedback

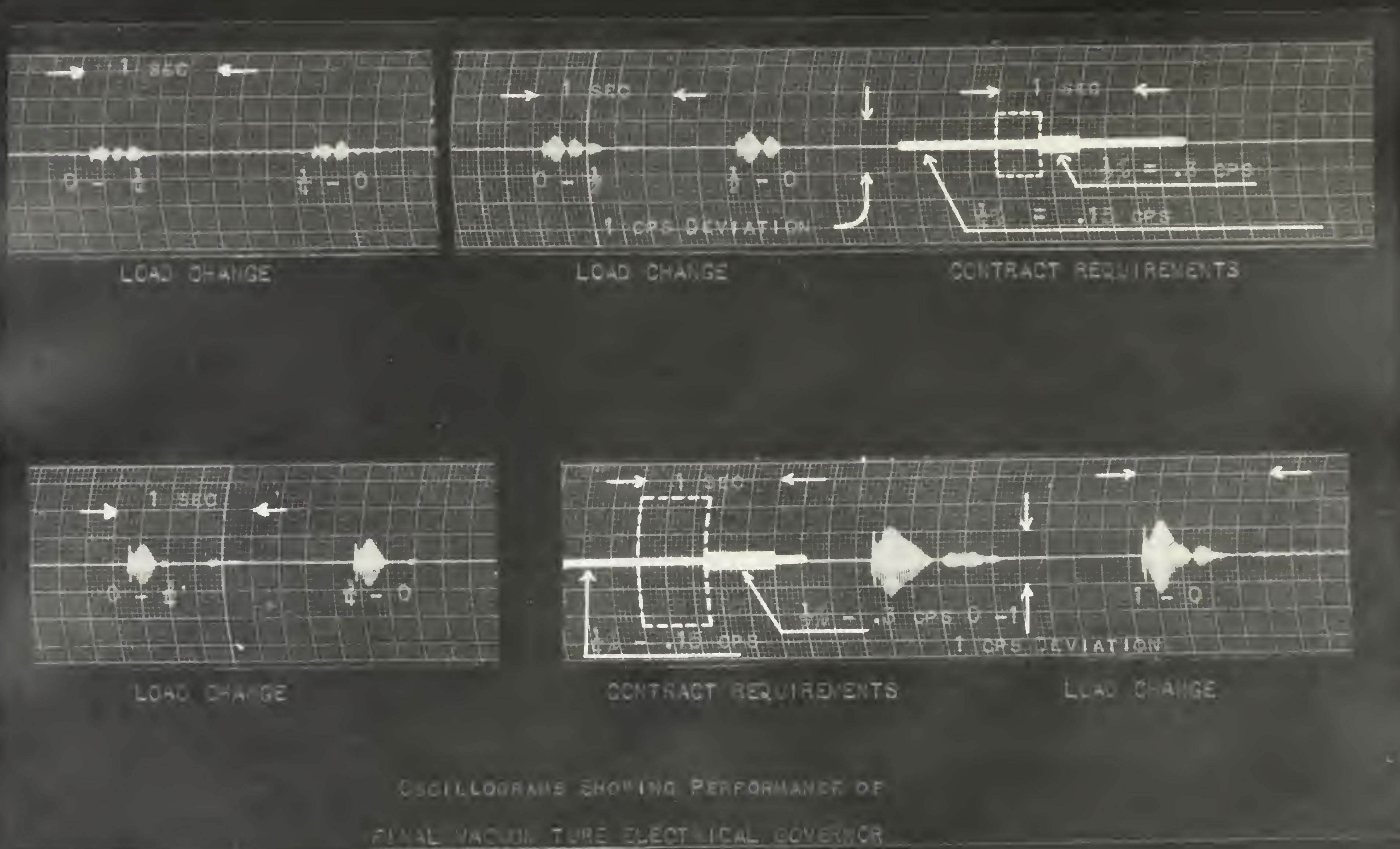


Figure 6.

Courtesy of Industrial Research Laboratories

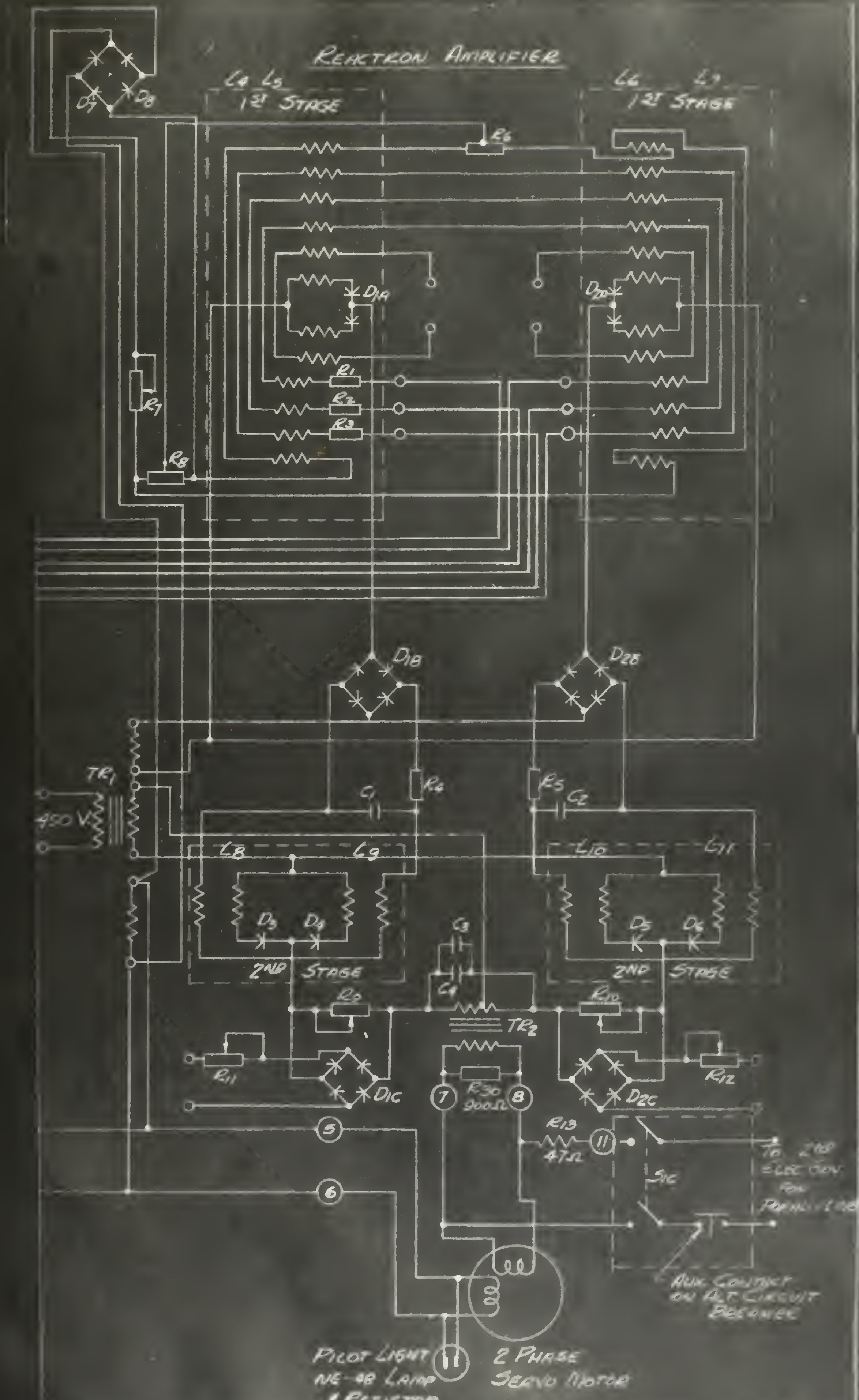


Figure 7.

Courtesy of Industrial Research Laboratories

circuits were connected, whereupon the throttle moved over to full throttle position and stayed there. A Ward Leonard representative was called in and he reported the amplifier satisfactory except for the feedback circuits (which had not been required in IRL's specifications) which he advised against using.

Further tests were run, making various changes to the circuits in an attempt to eliminate or reduce the instability. During the course of these tests, it was discovered that there was some reduction in instability by removing the integrating network from the tach loop, and a further reduction of instability by introducing a derivative network, i.e., feeding back a signal (approximately) proportional to the second derivative of servo motor position. Figure 8 shows the final tach loop circuit. A few minor adjustments to the circuits resulted in the best operation of the system, figure 9, incorporating the magnetic amplifier. The system is stable, i.e., has damped oscillations, but only for the most critical adjustment of frequency detector and tach loop input amplitudes. Too much frequency detector input or too little tach loop input result in instability, i.e., continuous hunting of the throttle. Too little frequency detector input results in maloperation; the throttle drifts up against the stop at one end or the other of its throw. Too much tach loop input results in excessive damping, i.e., long response times. Even at the optimum settings the operation is not within the specified limits.

This investigation was undertaken on the understanding that the governor would be turned over to the Navy early in January of this year. IRL had already received two extensions on their contract and I was assured that no further extensions would be allowed. However, further

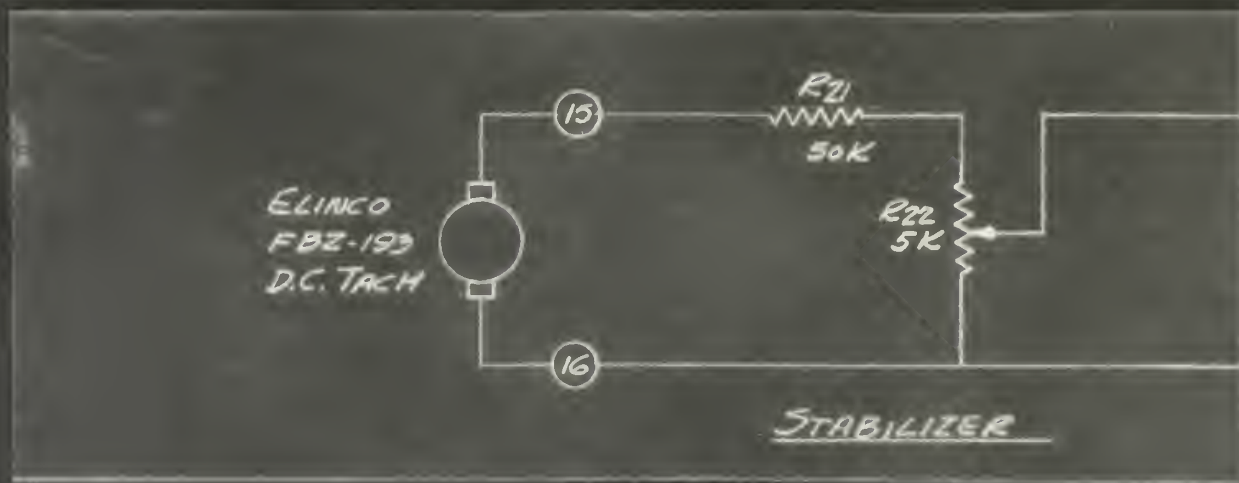
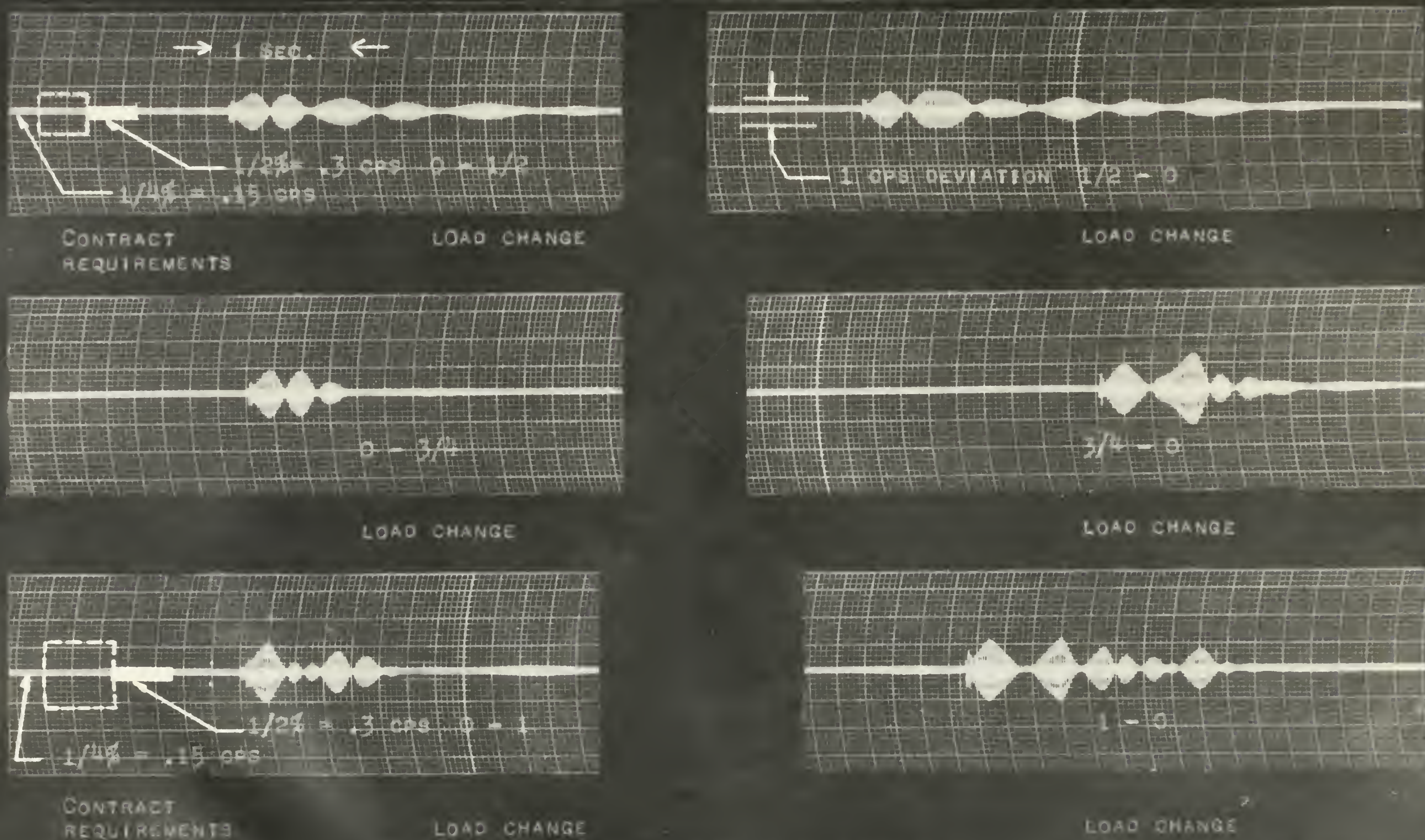


Figure 8.

Courtesy of Industrial Research Laboratories



BRUSH OSCILLOGRAMS OF MAGNETIC
AMPLIFIER GOVERNOR OPERATION
Figure 9.

Courtesy of Industrial Research Laboratories

extensions were granted and the governor has not yet been delivered to the Navy. This resulted in the fact that I was unable to run any tests on the system until the last week in April. Also I have not been able to make any changes or adjustments in the system, except where such have been provided for by variable resistors and potentiometers, or make or break any connections except where terminal strips exist for fear of breaching the contract. I do not wish to infer that the personnel at Industrial Research Laboratories have not been extremely helpful in giving aid whenever possible, but rather that due to the constant changes the equipment has been undergoing it has never been available as a complete unit for testing.

CHAPTER II

INVESTIGATION

It was felt by the writer that on the basis of previous operation a logical starting point would be an attempt to track down the source of the 3 to 5 cycle oscillations observed, see figure 9. The first step contemplated was to check the response of the amplifier through a range of frequencies from about 0.5 to 10 cycles. However, no signal generator capable of generating these frequencies with sufficient amplitude when connected to a 5000 ohm load was available.

A Packard-Hewlitt model 200-B audio oscillator was converted to operate in the range desired. As designed, this Wien bridge oscillator has a minimum frequency of 20 cycles. The oscillator covers a frequency span of 1000 to 1 in three ranges by using "R" circuits composed of three decade resistors with a selector switch and "C" circuits composed of variable condensers covering a capacity spread of 10 to 1. At the 20 cycle frequency the RC circuits contain 8.5 megohms and about 1000 micromicrofarads, respectively. 0.01 microfarad capacitors were shunted across the variable condensers and provision made for the insertion of external resistors in series with the decade resistors.

With this capacitor arrangement the frequency range is no longer continuous, the variable capacitors giving a spread of about 1.1 to 1. However, this spread plus the range selector and use of standard RTMA value external resistors allows the selection of almost any frequency from 0.4 to 1800 cycles. Leakage resistance in the capacitors and capacity in the resistors and associated wiring limits the lowest frequency at which the oscillator will operate.

The negative feedback circuit had to be modified to allow oscillations at the lower frequencies. The original feedback resistor was replaced by a larger resistor shunted by a variable resistance. In this way the negative feedback could be varied to values both above and below that of the original design. It was found necessary to vary this feedback for frequencies below about 2 cycles not only to find a value at which oscillations would occur but to find an optimum value which would produce good wave form.

The amplifier section following the oscillator stages had little gain at the low frequencies desired. Coupling condensers were replaced with larger value and, since high frequency response was not required, load resistors were also replaced with higher values.

The biggest problem was getting the low frequency signal out of the oscillator unit with no d-c content. Since it was desired to feed this signal to a 5000 ohm circuit the use of a blocking capacitor for 0.5 cycles was out. The oscillator had a transformer output, but this transformer would not pass any frequency below 2 cycles without over 90% attenuation.

The output stage (single ended 6V6) was changed over to a cathode follower using the original 800 ohm resistor. A low frequency pi filter (utilizing the now unused output transformer) was inserted in the return side of the power supply and connected to ground through a 1000 ohm variable resistor. All tubes in the oscillator except the 6V6 drew a total of about 36 milliamperes so that a negative bias variable from 0 to 36 volts was obtainable. The grid and cathode resistors of the 6V6 were returned to this bias point. Since the 6V6 developed about 27 volts

across its cathode resistor it was possible to adjust the cathode follower output to zero d-c level. With this arrangement it is possible to obtain a 14 volt peak-to-peak signal from the oscillator at 0.5 cycles when connected to a 5000 ohm load.

This oscillator was then connected to the frequency detector input of the magnetic amplifier, the other two inputs being left deenergized. Output readings were taken across the control phase terminals of the servo motor. With the oscillator set for the lowest frequency and the d-c balanced to zero in the output, the amplitude was adjusted to 2 volts peak-to-peak. The amplifier output was found to be badly unbalanced. Feeling that perhaps the input still contained some residual d-c an attempt was made to balance it out by observing the output waveform. In doing this two things were noted. First, the amplifier is extremely sensitive to bias unbalance, or d-c in the input, as little as 0.01 volts causing a visible amount of unbalance in the output. Second, with the output balanced, the oscillator indicated 0.2 volts d-c at its output. This meant that the amplifier bias circuit was not balanced (adjustment of resistor R8). The setting of this resistor was changed to give as nearly perfect balancing as possible.

At this point it was decided that, for the purpose of the tests to be made, the bias would be balanced roughly at R8 and that any further balancing required would be accomplished by adjustment of the d-c content of the oscillator output, since it makes no difference whether the d-c ampere turns are applied to the core by the bias or control windings.

It might be mentioned here that considerable difficulty was encountered in obtaining d-c voltage stability wherever d-c occurred. The d-c component of the oscillator drifted, the bias balance of the amplifier

drifted, the balance of the Brush recorder amplifiers drifted. This caused a large portion of the time spent on this project, about 50 to 70%, to be wasted in waiting for the cricuits to warm up and steady down, in making adjustments to the circuits, and in rerunning recordings which were spoiled by a drift in one or more of these balances immediately before or during a run.

Also appropriate at this point might be the fact that all the adjustable resistors and potentiometers, R7, R8, R9, and R10 are power type resistors, wire wound on ceramic forms with a sliding, screw tightened clamp for the variable terminal. While this type of unit is excellent for factory adjusted models, it does not lend itself to the constant and critical adjustment required for test runs of the type made.

With the amplifier balanced as closely as possible, Run A, amplifier output at varying input frequencies, was made. The results of this run are compiled in Table 1, gain and phase shift are plotted against frequency in figure 10, and Brush recordings of the runs are included in Appendix I. The bias value designated in this and following runs as "previous optimum" is that value of bias which was found by IRL to give best results for overall governor operation.

An inspection of figure 10, reveals that the phase shift is 90° at 4.15 cycles and that the voltage gain is reduced to 70.7% at 4.40 cycles. Phase shift values are accurate to about 1/8 of a 60 cycle wave or 0.0020833 seconds. At 4 cycles this represents 3°; at 5 cycles, 3.75°. Gain values are correct to about 0.02 on the per unit basis. Since gain and phase shift values fall within this error overlap, it may be said that the half power point, or point of 90° phase shift occurs at a frequency of 4.3 cycles for this amplifier. This is significant since it

Table 1

Run A

Amplifier output versus input frequency

"Previous optimum" bias   No feedback

Input: 2 volts peak-to-peak

Input frequency cycles / second	Relative Gain	Phase shift Degrees lagging
0.419	1.00	11.33
0.719	1.00	17.25
1.019	0.96	24.46
1.690	0.95	41.63
3.869	0.76	81.54
5.078	0.62	106.99
6.818	0.52	122.73
8.338	0.24	135.08

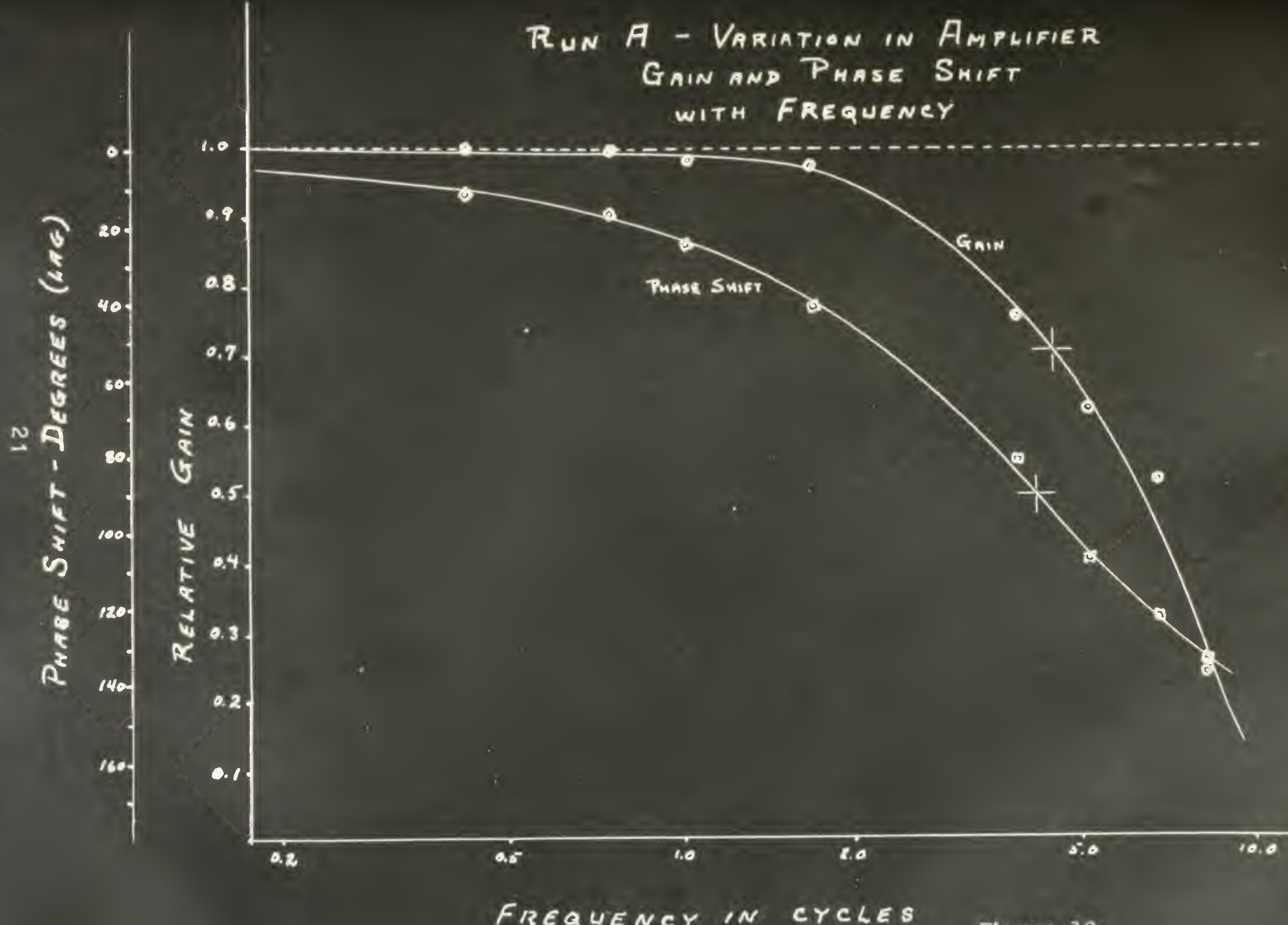

RUN A - VARIATION IN AMPLIFIER
GAIN AND PHASE SHIFT
WITH FREQUENCY
GAIN
PHASE SHIFT
PHASE SHIFT - DEGREES (LAG)
0
20
40
60
80
100
120
140
160
RELATIVE GAIN
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.2
0.5
1.0
2.0
5.0
10.0
FREQUENCY IN CYCLES

Figure 10.

falls within the 3 to 5 cycle range of the damped oscillations in the system occurring following a stepwise change of load.

The second series of readings, Run B, for tachometer network output at varying frequency was made in a similar manner to Run A. In this case the output was read at the output terminals of the tachometer loop; however, this loop was not connected to the amplifier input. Due to the fact that at certain frequencies the throttle hunted at large amplitudes and struck the stops, it was not possible to hold the input signal at constant amplitude on all runs. Brush recordings of the runs are included in Appendix I. In some respects these runs were quite inconclusive. Since input amplitude was not held constant, accurate gain measurements were not possible. Although the phase shift showed a general increase with frequency, the individual values fluctuated so widely as to be meaningless.

However, these tests indicated one point of importance, this being the natural resonant frequency of the servo motor - tachometer system with its attendant gear train, throttle rod and fuel rack. This frequency, which is about 4.45 to 4.50 cycles per second, is most obvious in runs B1 and B3, but may also be determined from B2 and B4. Apparently, at frequencies less than the resonant frequency, the oscillations are caused by a tendency for the gears and/or control rod to stick when, being stopped, they are subjected to a control force in one direction by the servo motor. When sufficient control force is applied to overcome this "static friction" the system breaks free and breaks ~~free and breaks~~ into oscillation. Run B1 indicates clearly the reasons for this deduction. At frequencies greater than one cycle it would seem that the mechanical

system does not pause long enough at the end of a throw for the oscillations to damp out and hence they are continuous from one cycle to the next. Again this frequency is significant since it is approximately the frequency of the damped oscillations of the governor system and is also close to the frequency at which the amplifier shows a 90° phase shift.

The third run, Run C, amplifier output at varying input frequencies, is similar to the first except that in this run the tachometer loop was connected to the amplifier for a portion of each run. Brush recordings of this run are included in Appendix I. Results are in line with what would be expected on the basis of runs A and B. At very low frequencies (C1) the tach loop feedback is of the correct phase to reduce output, but due to the presence of the (unbalanced) tach loop resonant frequency the output is so badly distorted as to bear no relation to input. C2 shows the same effects but the distortion is somewhat reduced and is now symmetrical since tach loop oscillations are now occurring over the entire (signal) cycle. In C3 the gain is still reduced, but the distortion is almost gone; the included recording was cut too short to indicate this well, but succeeding waveforms are the same as the last complete half cycle shown. C4 indicates that although the frequency is about one half cycle below the point at which the amplifier phase shift reaches 90°, positive feedback is present and the output increased. C5, C6 and C7 all indicate positive feedback, since output is increased over that obtained without the tach loop. However, this effect is greatest in C5 and decreases as the higher frequencies get further from the resonant frequency of the tach system.

The large positive feedback occurring at roughly the frequency of

oscillation of the governor system was felt to be the cause of this instability. It was reasoned that if either the natural frequency of the tach system could be raised or the time constant of the amplifier reduced, the oscillations could be made to occur at a higher frequency. Since the oscillations tend to damp out after half a dozen cycles or so, this would bring the governor response within the required specifications.

Since the time constant of the tachometer - servo motor system is apparently mainly that of the mechanical system tied to it there was nothing the author could do about this part of the system. However, there was the possibility of decreasing the time constant of the amplifier. The three input circuits had adequate reserve power so it was decided to determine if the feedback loops could be made to function properly and, if so, to see whether the feedback would appreciably reduce the time constant.

Before an attempt was made to operate the amplifier with feedback, runs were made correlating feedback output versus amplifier input and output, Run D. Run D1 shows the relation of the feedback output from one side to input, D2 the same feedback versus amplifier output. D3 shows the relation of feedback output from the other side to input. The input signal was 2 volts peak-to-peak for all runs, bias was the "previous optimum" and the feedback loops were open. Input frequency was 1.728 cycles.

It will be noted that the signal components of the feedback outputs are 180° out of phase with one another as would be expected. Both lag the input by approximately 90° and both contain a d-c component of the same polarity. The polarity of test leads was carefully maintained in

these runs. The feedback output is badly distorted but contains a definite a-c component at input signal frequency.

Although not directly connected with the first three tests, Run D4 is included at this point to indicate the result of some tests made to determine the effect of bias on feedback characteristics. When bias was changed, a definite transient unbalance was observed in the amplifier output. Run D4 shows this effect at its worst, when bias is changed from zero to maximum value. Although the amplifier was not perfectly balanced, the change in balance with the change in bias is obvious. Noteworthy is the time, approximately eight seconds, required for this transient to die out.

Next the feedback loops were connected as indicated on the manufacturer's circuit diagram. With this connection the amplifier apparently was operating at such a point on the saturation curve that saturation and desaturation did not occur for any value of input signal. D5 shows amplifier output with no feedback and no bias. D6 shows the effect upon output when feedback loops are connected. D7 is the same as D6 except that bias is now adjusted to the "previous optimum". With feedback loops connected in this manner an unbalance in the system is indicated since the phase of the amplifier output remains unchanged as the input signal changes polarity.

The purpose of Run E was to determine the effect upon amplifier output obtained by connecting the feedback loops in manners other than indicated by the manufacturer. Two different configurations were used; in the first, the feedback connections were reversed in polarity, in the second, the feedback loops were crossed bringing feedback output from one second stage core to the opposite input stage core and vice versa. All runs were made at 5.062 cycles at a voltage of 1.6, peak-to-peak. E1

indicates amplifier output when operating without feedback or bias. E2 shows the effect of reversed parallel feedback on amplifier output. It will be noted that the amplitude of the output is reduced. However, at this point it is impossible to say whether this is due to negative feedback or the change in operating point caused by the biassing effect of the d-c component in the feedback. E3 shows the effect upon output when bias is used with this feedback connection. Note that the amplifier is now unbalanced to a point where there is no phase change in the output and the amplitude reaches only one maximum per input cycle. It is particularly to be noted that this effect did not occur with this feedback connection when no bias was used. E4 shows amplifier output with the criss-cross feedback connection. As in E2 the amplifier output is reduced in amplitude and again it is impossible at this point to determine definitely the cause of this reduction. Although no Brush recording was made of it, a run was made using criss-cross feedback with "previous optimum" bias. The amplifier output in this instance was so badly distorted as to bear no relation whatever to input.

Due to the effect caused by variation in bias when feedback was used, it was decided to make a series of tests to determine the effect of variation in bias upon amplifier output when no feedback was used. Run F shows the results of these test which are tabulated in Table 2 and Brush recordings of which appear in Appendix I. The bias points used were obtained by arbitrarily dividing resistor R7 into six sections. The seven points thus obtained with the bias circuit connected, plus another with bias disconnected, comprised the eight values used in Run F. An input of two volts peak-to-peak at 5.070 cycles was used throughout.

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Gain was greatest at the minimum bias setting and decreased steadily with increasing bias. Phase shift values varied but showed no consistent trend with bias or gain.

Run G was made in an attempt to determine some of the characteristics of the amplifier using both bias and reversed parallel feedback. Again all tests were made with a 2 volt peak-to-peak input at 5.070 cycles. Brush recordings of this run appear in Appendix I. The bias used throughout this run is the minimum bias (point 1) of Run F. G1 shows amplifier output with bias and no feedback. For comparison G2 shows output with the feedback windings connected. G3 shows the effect on output when the tach loop is connected, with both feedback and bias. It should be noted that the addition of the tach loop causes the output to become symmetrical again. G4 is merely a repetition of G3 on a time scale which allows comparison of output with and without the tach loop.

Since the output when using both feedback and bias, but no tach loop, appears to be unbalanced in the same manner as results when a d-c component is present in the input or the bias to the two input cores is not balanced, it was decided to attempt to remove this unbalance by varying the d-c component in the input. When this was attempted, it was found possible to introduce a large d-c component into the input with no apparent change in output unbalance. However, with the addition of very little d-c beyond this point, the amplifier passed through a region of instability wherein the output shifted toward a balanced condition and then flopped over to a condition of unbalance 180° out of phase with the initial condition. This same phenomemon then occurred when the d-c component in the input was varied in the opposite direction. G5 illustrates this effect.

Table 2

Run F

Amplifier output with varying bias

Input: 5.070 cycles 2 volts peak-to-peak

No feedback

Bias	Relative Gain	Phase shift Degrees lagging
None	1.00	89.9
pt 1 (minimum)	1.89	82.1
pt 2	1.82	83.8
pt 3	1.78	79.2
pt 4	1.62	80.6
pt 5	1.24	85.3
pt 6 (previous optimum)	0.95	80.6
pt 7 (maximum)	0.53	82.1

AMPLIFIER OUTPUT WAVEFORM

with no feedback and no signal

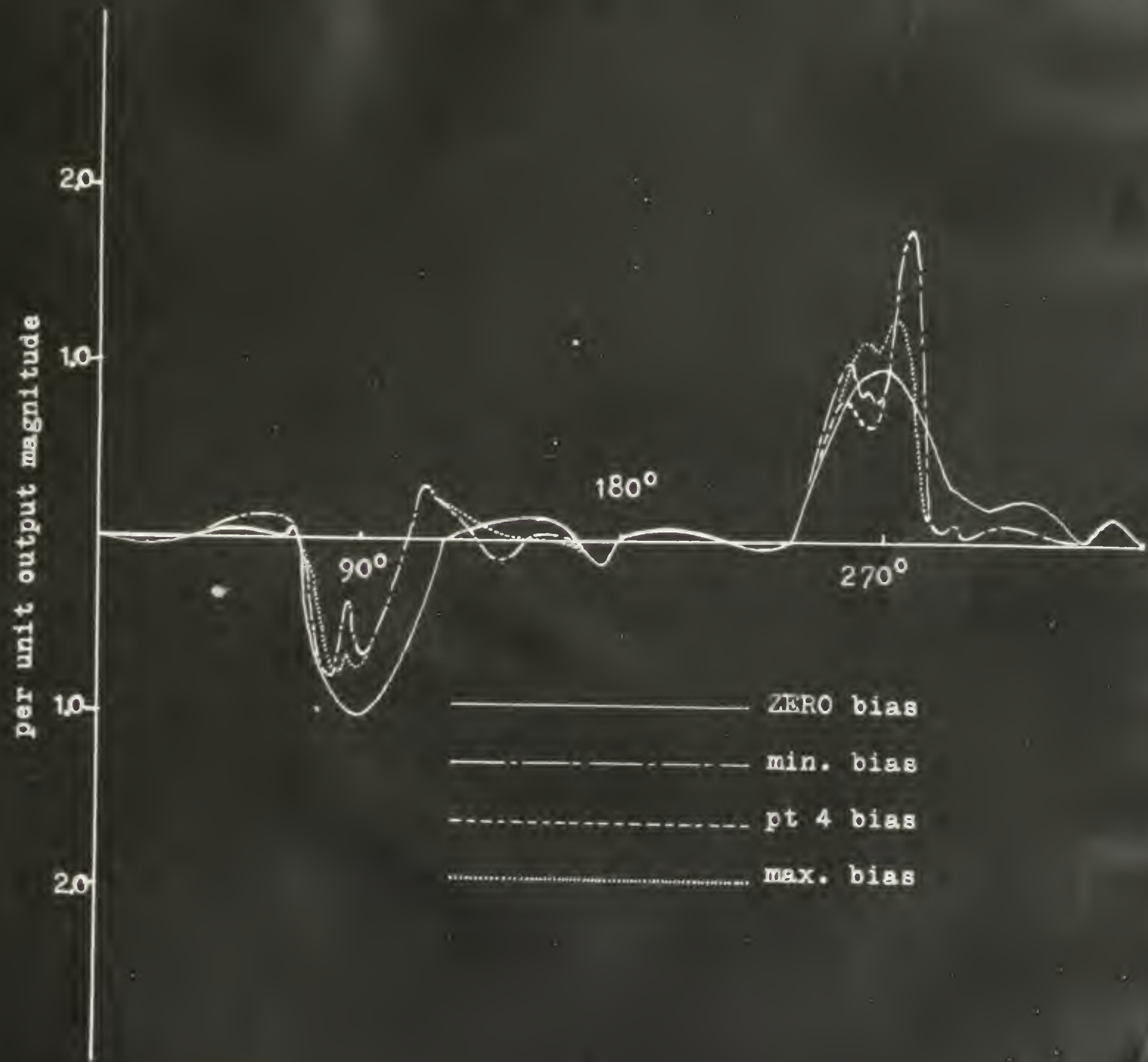


Figure 11.

AMPLIFIER OUTPUT WAVEFORM

with signal but no feedback

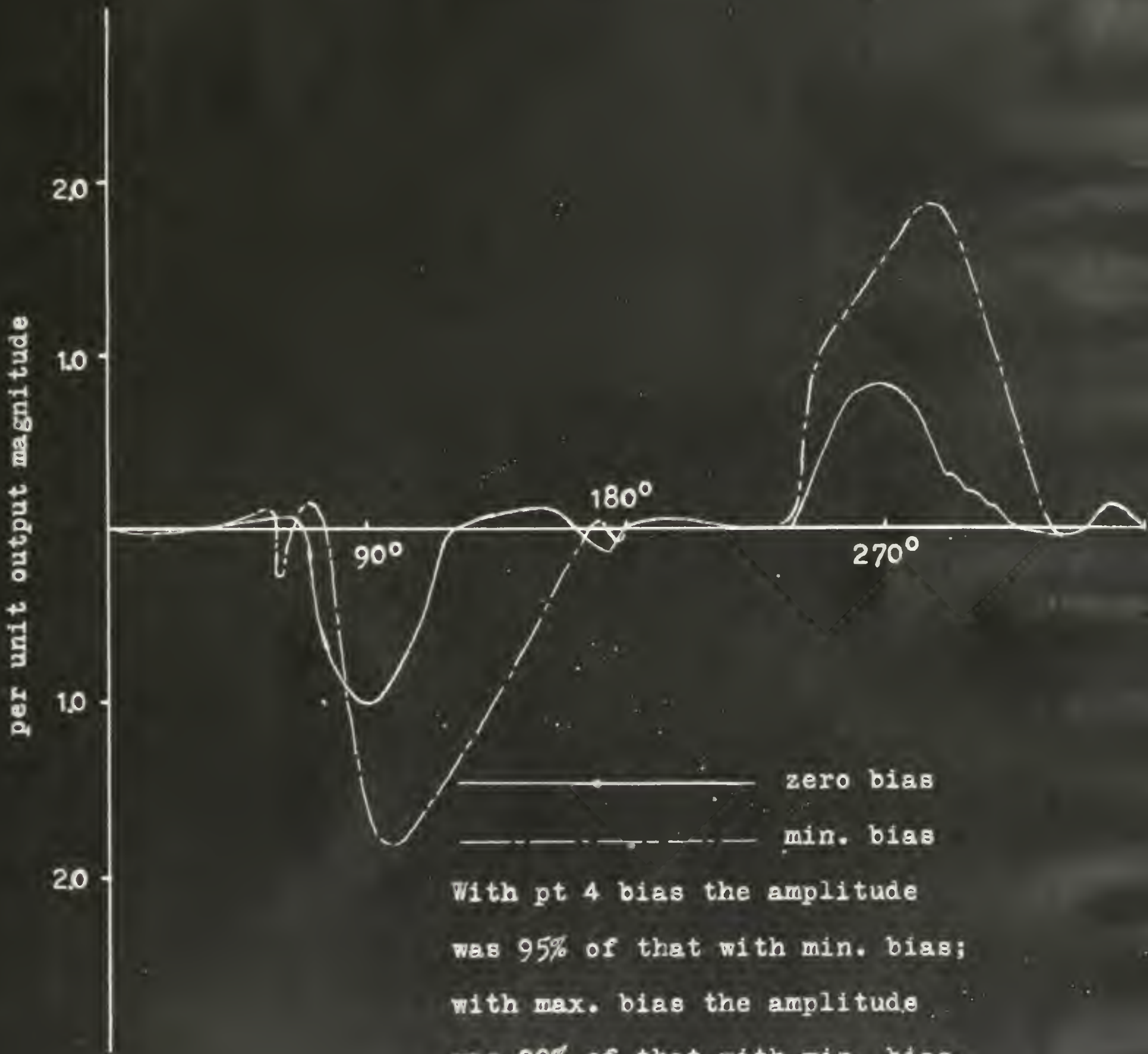
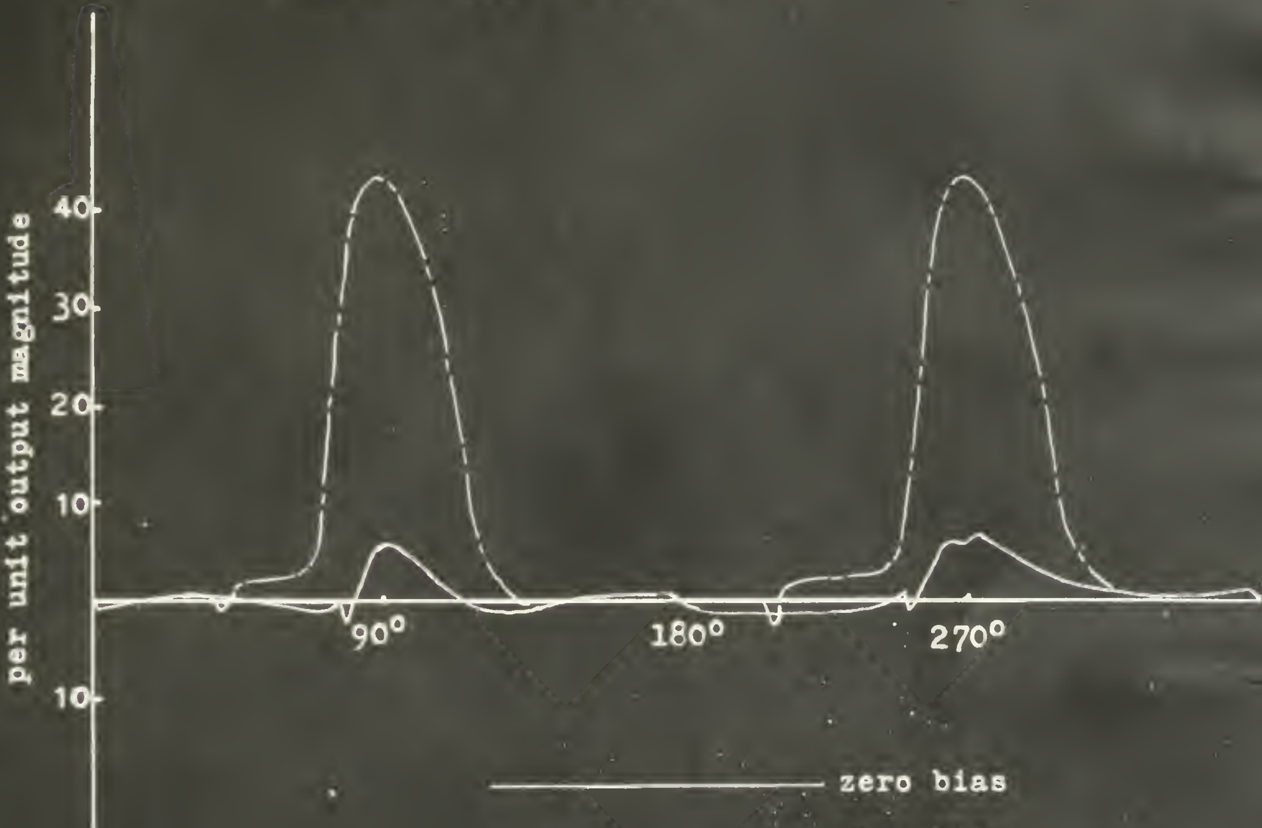


Figure 12.

AMPLIFIER OUTPUT WAVEFORM

with feedback and signal



With pt 4 bias the amplitude was 115% of that with min. bias; with max. bias the amplitude was 120% of that with min. bias. In each case the waveform was the same.

Figure 14.

CHAPTER III

DISCUSSION

This started out as the investigation of an electric governor system; it rapidly degenerated into the task of determining why a two stage magnetic amplifier, supposedly designed for the circuit in which it was connected, did not function properly; this determination to be made without being able to get any further into the amplifier than the input and output terminals.

This entire investigation has been based upon the damped oscillations, i.e., hunting, that the system exhibits. Unfortunately the illustration of this hunting, figure 6, is one of the best tests that IRL had; recordings of other tests when the oscillations would not damp out, which would have been useful in a more exact determination of frequency of oscillation, were no longer obtainable when I tried to get same for inclusion in this thesis.

Two other points warrant elaboration here. The response characteristic of the frequency detector, figure 3, is unbalanced. This is not the result of poor design, but was done deliberately to improve system operation. When a load is thrown on the generator and it starts to slow down, the inertia of the system is greater, due to the electrical loading of the generator, than when the generator is running light, i.e., when load has been dropped off the generator. Thus, with a balanced frequency detector, the system tends to be less stable when the load is dropped than when it is applied. By increasing the output at higher frequencies, i.e., when the generator starts to speed up, the system tends to balance out this difference in response and give equivalent results for a load

either applied or removed.

Figure 8 supposedly illustrates the tachometer circuit with a derivative network, but the latter is not apparent in this drawing. This is because the derivative network is an RL circuit and the inductance is that of the input winding on the magnetic amplifier. This system is not particularly desirable, in my opinion, since this inductance varies as the input core of the magnetic amplifier saturates. Since this saturation is caused by the total instantaneous ampere-turns from the three control circuits, this device makes any analysis of the operation of the tachometer loop almost impossible.

The time constant of the tachometer - servo motor system could be decreased if the overall torque to inertia ratio of the system could be increased. This could be done by using a different servo motor, which when connected to the system, would give a larger overall T/J ratio and/or by increasing the gear ratio between the servo motor and the fuel rack. As I see it, there is no way to reduce the inertia of the throttle rod, fuel rack and injectors; this is a characteristic of the prime mover, not the governor.

All of which bring up the point that this governor is being designed for the specific prime mover - generator combination upon which it is being tested. It has yet to operate within specifications, but may be brought to do so by slight refinements to the control circuits and critical adjustment of the amplitudes of these inputs. However, if this same governor is applied to a different prime mover - generator combination where the inertia of the fuel rack, the throttle characteristic of the prime mover and the inertia of the prime mover and generator are different, the system may work but the chances are as great that it will

not. Should all these variables operate in such a direction as to affect operation adversely, this governor never could be made to operate satisfactorily without complete redesign of the entire system including the magnetic amplifier.

The magnetic amplifier, with its long time constant (relative to a vacuum tube amplifier) and its effect, by the introduction of a variable parameter, inductance, on control circuit characteristics, becomes the focal point in the design of the entire system.

Generally speaking, the time constant of this magnetic amplifier is poor. It may be said that the 90° phase shift point occurs at approximately 5 cycles (signal frequency). This is equal to a 0.2 second time constant or 12 cycles of line (60 cycle) frequency. Vickers in their Magnetic Amplifier Design Handbook give a universal curve of optimum time constant in terms of line frequency versus power gain for single stage magnetic amplifiers without feedback. With a 2 volt peak-to-peak (0.707 volts rms) input into a 5000 ohm winding this amplifier delivers approximately 2 watts to the control phase of the servo motor. This represents a power gain of 20,000. There was no way for me to determine the individual gains of the two stages of this amplifier, but if it is assumed that the gain of the first stage is twice that of the second, then the gain of the first stage is on the order of 200, the second stage, 100. The Vickers' curve indicates a time constant of 3.5 cycles for a power gain of 200, 1.3 for a gain of 100. Since, the time constant of the two stage amplifier will be the sum of these two, again a first order approximation, this indicates a time constant of 4.8 cycles, considerably less than the 12 cycles observed. While this determination of time constant is based on many assumptions and is very approximate,

it does indicate that the time constant of the amplifier is greater than could be expected.

It must be considered, however, that the 4.8 cycle value is an optimum which is based on correct resistance to turns ratio in the control windings, well designed core laminations and good matching between amplifier and load. The control windings, including bias and feedback, are the controlling factor. The time constant for each winding is proportional to N^2/R, where N is the number of turns and R is the resistance of the circuit. As would be expected, the greater the resistance (relative to number of turns or inductance), the less will be the time constant. Since the control windings are in parallel magnetically, it can readily be seen that if one winding has a large time constant there is little use in trying to decrease the overall time constant by decreasing the time constants of the other windings. This is the case in this amplifier; the three control windings have high resistance (5000 ohms), but the bias and feedback windings with about half the number of turns have a total resistance on the order of 100 ohms. The core laminations and output circuit constitute a delay which varies from 0.5 to 2.0 cycles depending on design.

The lack of symmetry in the wave forms of figures 11 and 12 is an indication of poor design. These figures along with 13 and 14 and the recordings D4, D5, D6, D7, E2, E3, G1, and G2 supply the information necessary for determining approximate operating points and the polarities of bias and feedback. Figure 15 shows the output versus input characteristic of a stage similar to the first stage. The slope of this curve is gain. With no d-c input the operating point is a. With "minimum" bias the point moves to b, giving greater gain, while with "maximum" bias the point shifts to c, giving decreased gain. Other bias points lie between

MAGNETIC AMPLIFIER

STATIC CHARACTERISTIC

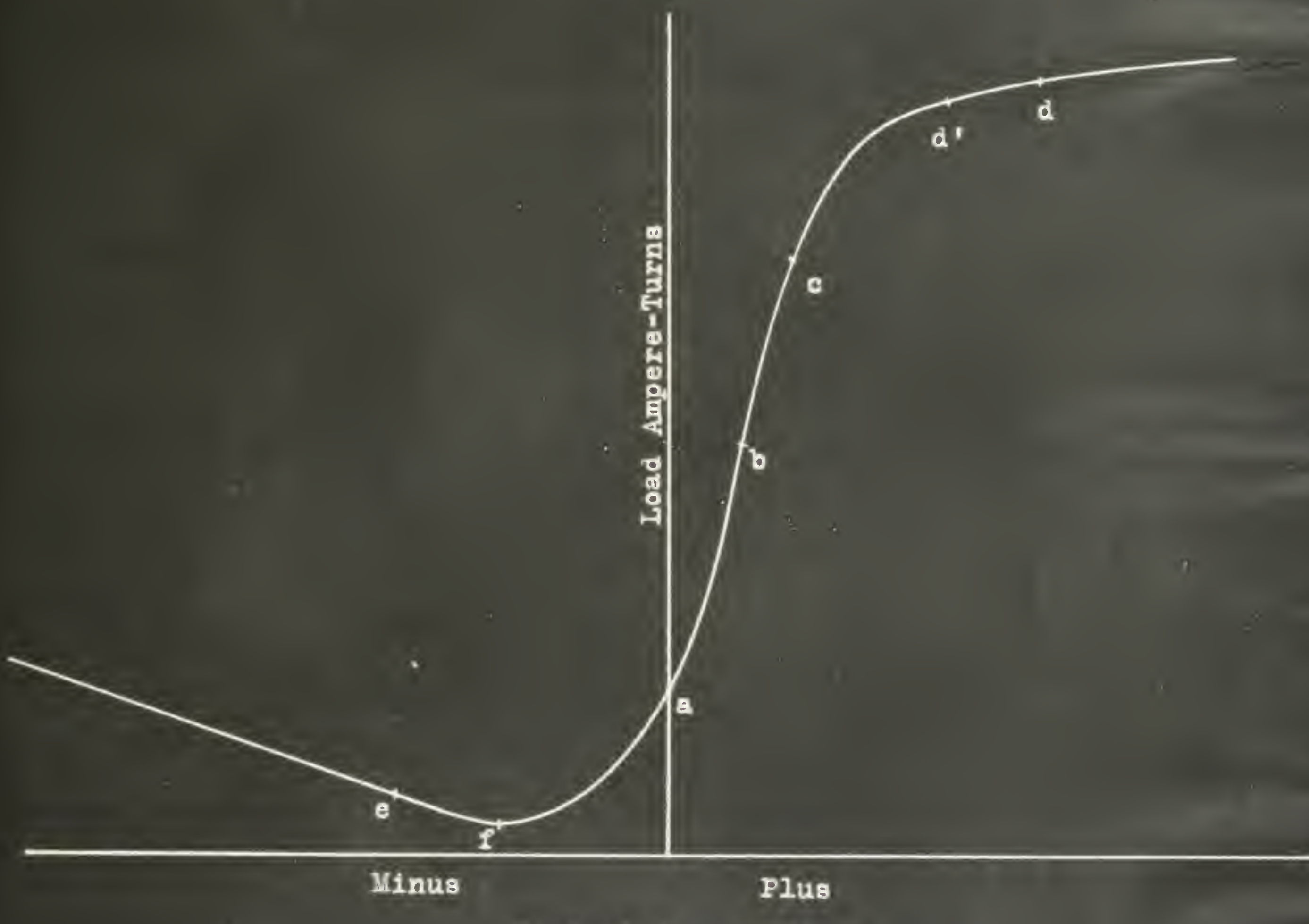


Figure 15.

b and c. This does not agree with the circuit diagram which indicates applied bias is negative with respect to self saturation. The d-c component of the feedback signal is in the same direction as the applied bias when the bias windings are connected according to the manufacturer's instructions. This agrees with the circuit diagram. With the feedback windings connected in this manner the operating point now moves to d. This causes operation in the saturated region giving very low gain. In addition, the feedback is negative which decreases gain even further. Even without bias, operation is in the saturated region, point d'. The steady signal a-c component appearing in the amplifier output under these conditions is probably due to a slight unbalance between the two sides of the amplifier which does not show up until the large saturation currents flow.

When the feedback circuits are connected with reversed polarity, i.e., reversed parallel feedback, and no bias, the d-c component moves the operating point to e. Under these conditions the gain is low but the feedback is positive which will tend to increase the gain. With bias applied under these conditions the operating point moves to a point such as f. With such an operating point the control signal will be rectified, i.e., a change in control signal in either direction will appear as a "positive" output. Gain in this region is very low but again the positive feedback tends to increase the gain.

The first stage with its three control windings plus bias winding plus, possibly, feedback winding will tend to have a long time constant in any event. It might be advantageous to use a low gain (say 10) stage at this point to give a small time constant, followed by two stages of self biased amplification. Actually three stages of amplification should

not be required if control input powers were increased. At 62.4 cycles (the maximum deviation allowed under the specifications) the output of the frequency detector is only 0.6 volts (0.42 volts rms); this is further decreased by the tach loop operation. This indicates an input power of about 0.000032 watts. If frequency detector input voltage were increased tenfold the power gain requirements of the amplifier would be reduced by 100, with attendant decrease in time constant. Since the frequency detector gets its voltage from the line through a transformer, the additional voltage may be readily obtained. The tach output voltage could likewise be increased by changing its location in the gear train between servo motor and throttle.

Another phenomenon which tends to cause instability in the system by causing non-linearity, is the effect of variation in line voltage. When the governor tends to hunt both line voltage and frequency vary. Frequency variation has very little effect on amplifier performance. However, raising or lowering the a-c supply voltage effectively raises or lowers the whole control characteristic, a 10% change in voltage causing about a 15% change in output current. Since bias comes from the same source the two effects are cummulative. Quoting Vickers......If (bias) is derived from the same a-c source which supplies the amplifier output circuit the amplifier output may be subject to transients with changing supply voltage.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

It is believed that the present governor system with no major modifications can be made to operate on the prime mover - generator combination to which it is applied at present. However, it is not believed that such operation will be reliable, nor is it believed that this governor can be applied successfully to many of the a-c generating units in operation aboard ship.

For general application, the magnetic amplifier should be designed to have a faster speed of response by adoption of one or more of the following (1) redesign of bias windings and cores, (2) inclusion of a workable feedback circuit, or (3) use of a three stage amplifier. The input circuits should be carefully redesigned for greater output and to minimize the effect of variable inductance in the input windings upon control signal characteristics. Inclusion of a voltage regulator between line and amplifier supply transformer is suggested.

The servo motor with its attendant gear train should be changed. A higher gear reduction from servo motor to load will reduce the inertia effect of the load reflected back to the servo motor; a motor should then be selected to give optimum torque to inertia ratio for the combination. Care should be taken in the construction of the gears and throttle linkage to avoid binding.

Setting aside, for a moment, the Navy requirements for this governor, it is felt that from a design standpoint a faster responding, more compact unit could be developed by going to a higher frequency, say 400 cycles, for amplifier and control circuit supplies. Not only would the amplifier

have a shorter time constant and be smaller and lighter, but the control circuits would also be smaller and lighter resulting from the use of physically smaller capacitors and transformers. Since power requirements for the system are low (25 to 30 watts) power could be obtained from a small generator direct connected (turbine drive) or geared (diesel drive) to the prime mover. In the case of generators operating at 3600 rpm, the exciter could conceivably be designed to also supply this a-c requirement.

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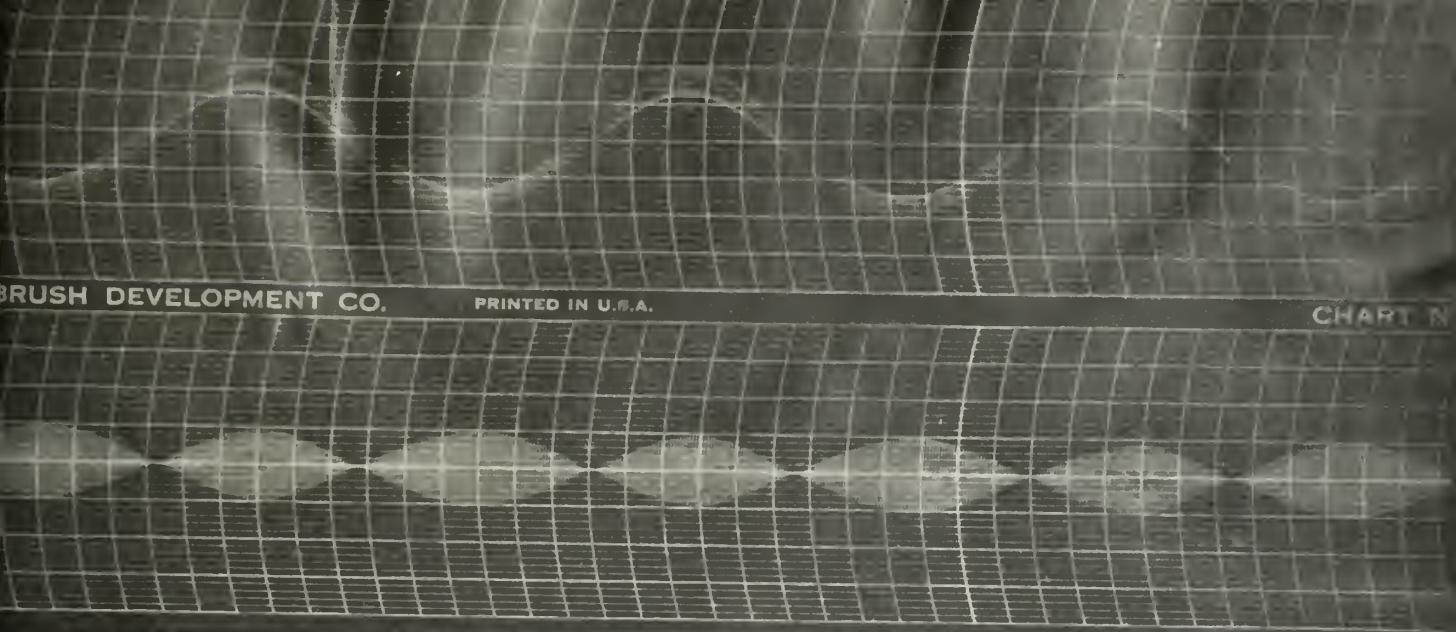
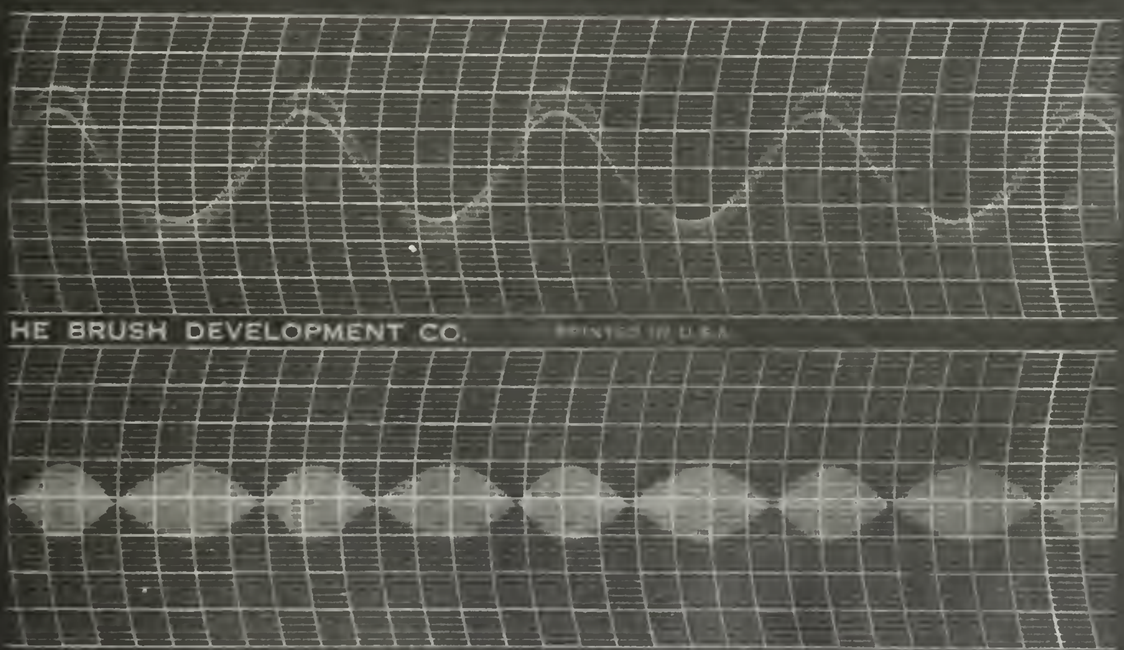
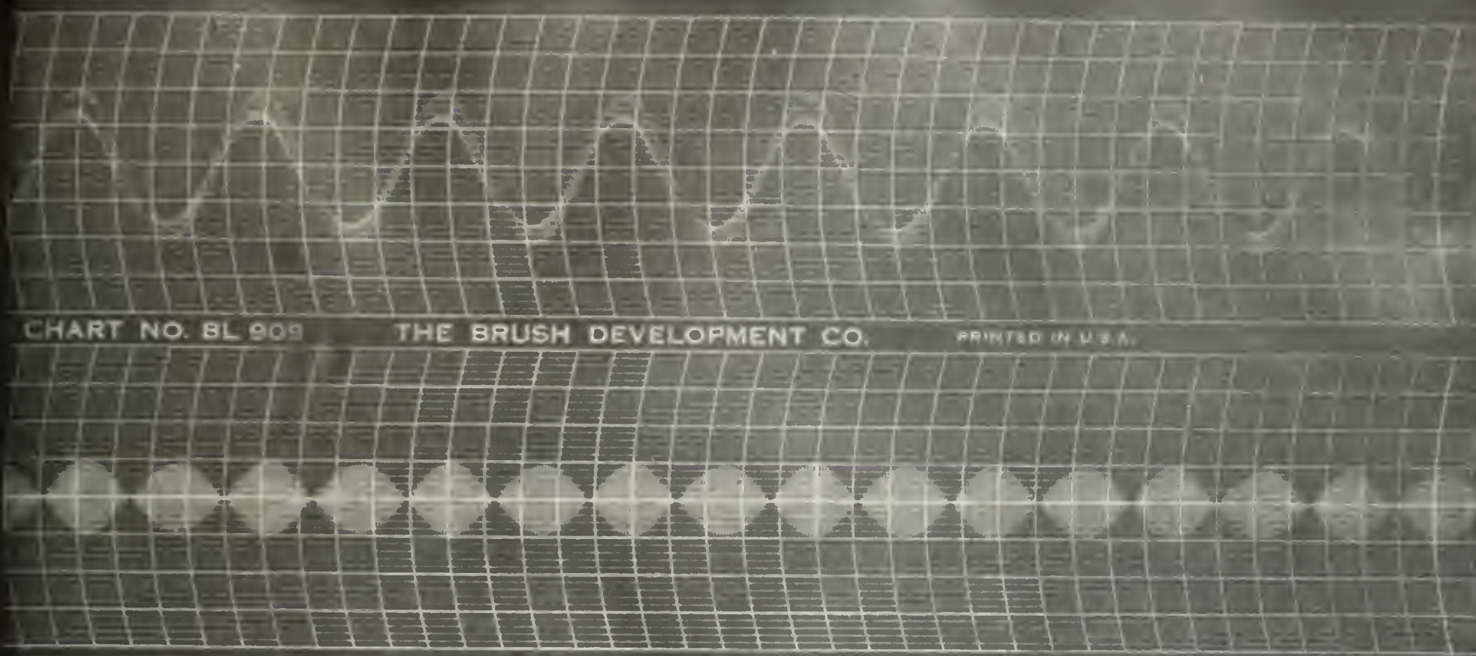


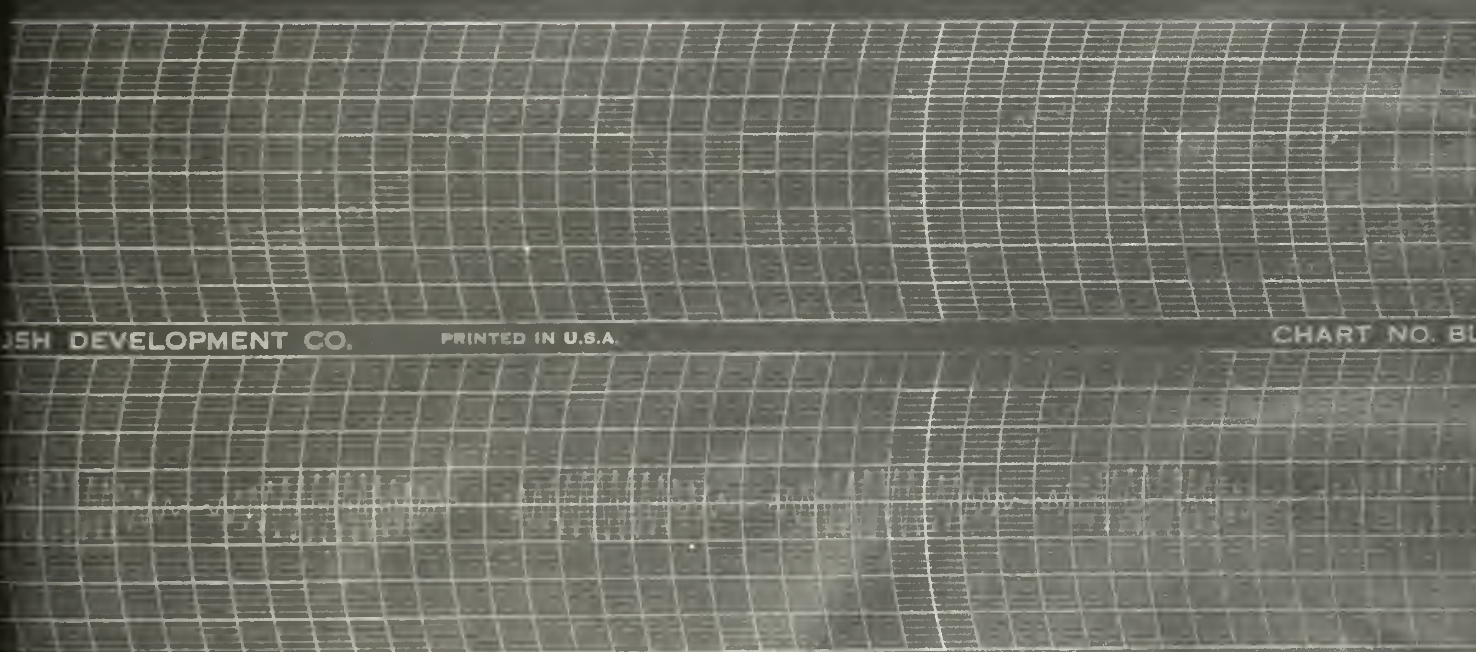
Run A1 0.419 cycles No feedback "Previous optimum" bias
Gain: 1.00 (reference) Phase shift: 11.33° lag



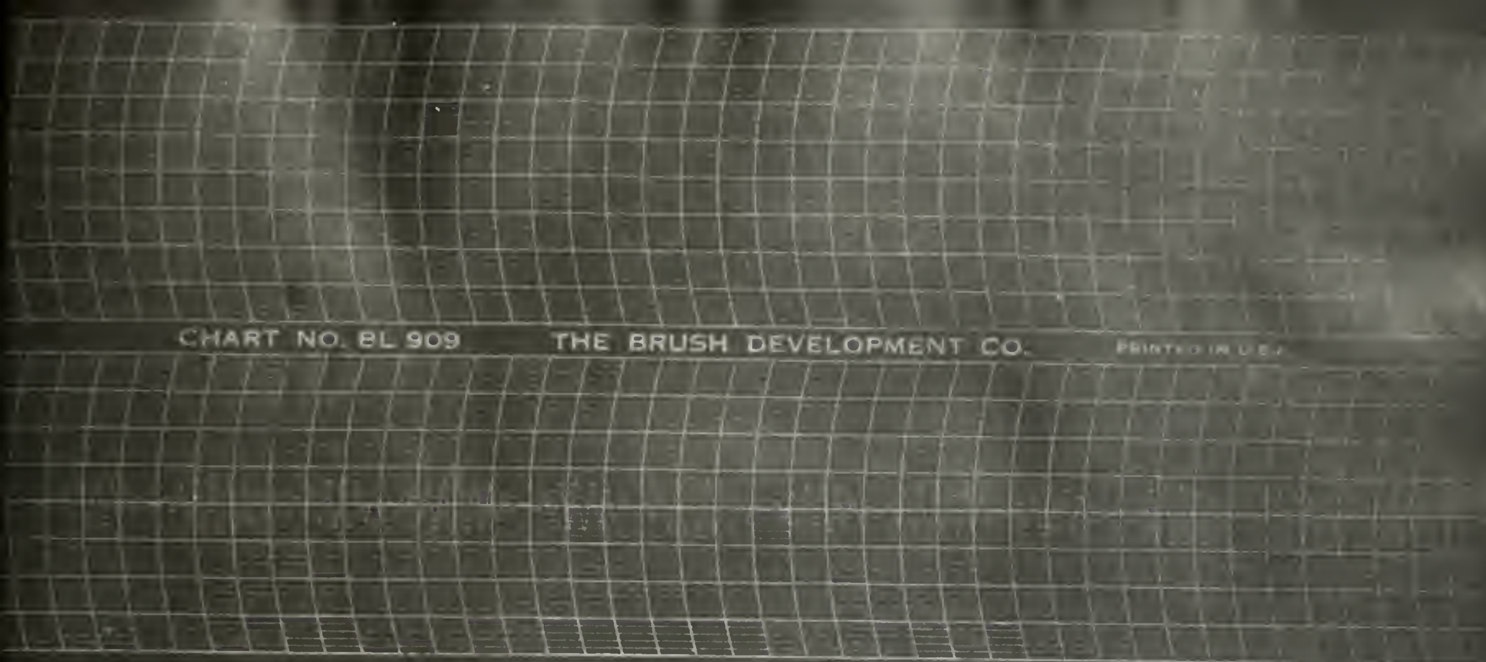
Run A2 0.719 cycles No feedback "Previous optimum" bias
Gain: 1.00 Phase shift: 17.25° lag



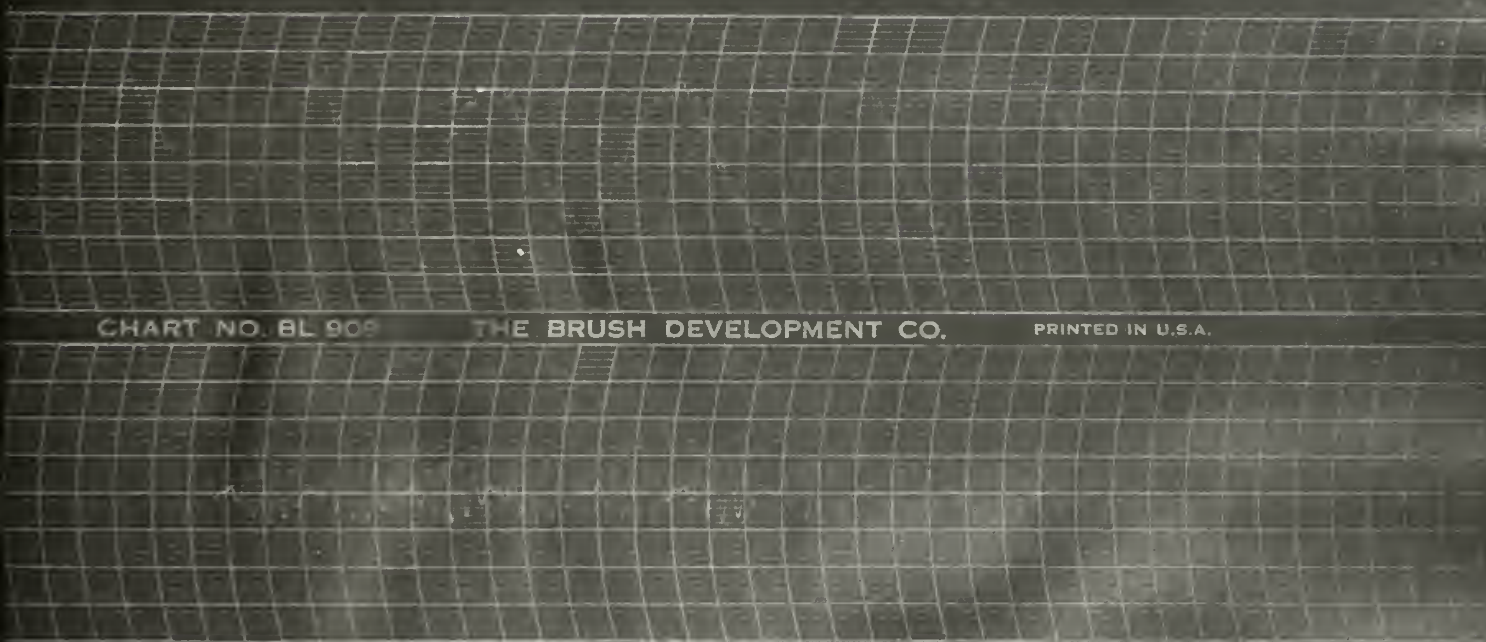
Run A3 1.019 cycles No feedback "Previous optimum" bias
Gain: 0.96 Phase shift 24.46° lag



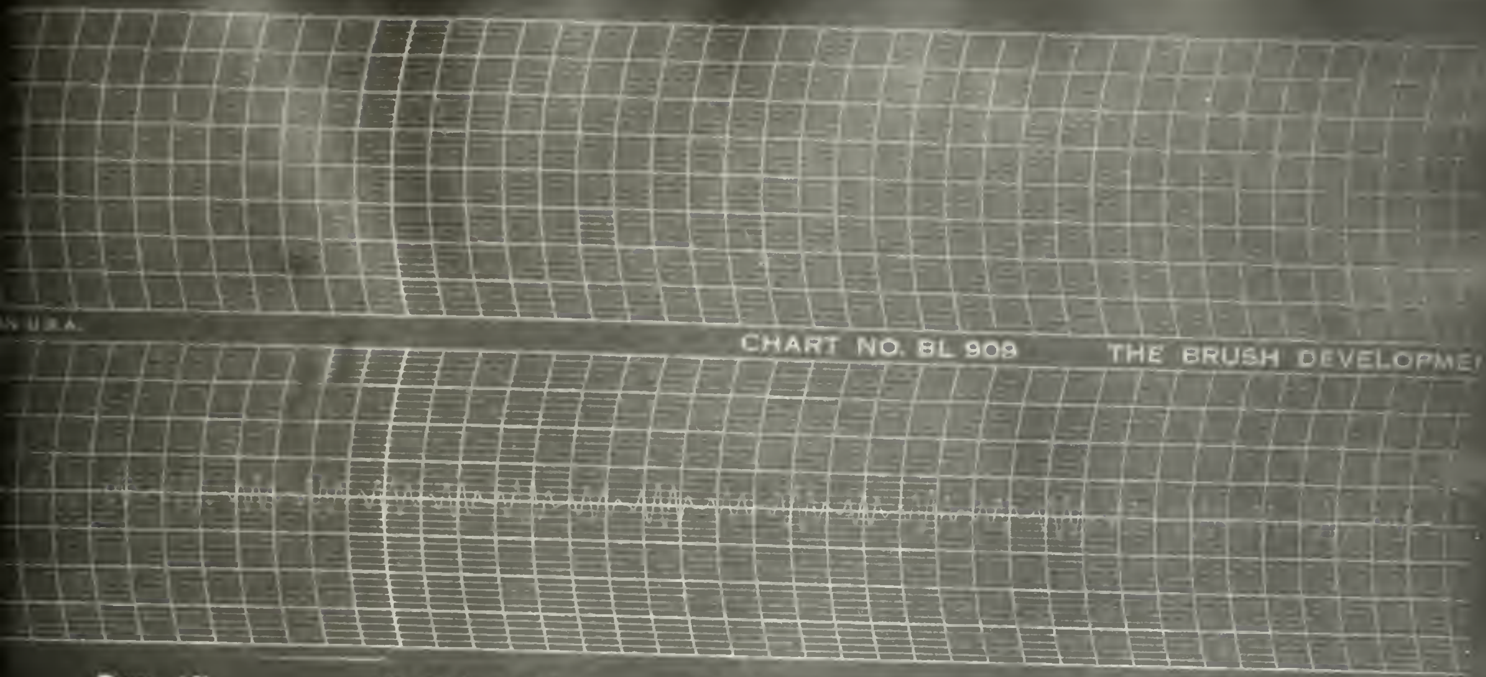
Run A4 1.690 cycles No feedback "Previous optimum" bias
Gain: 0.95 Phase shift: 45.63° lag



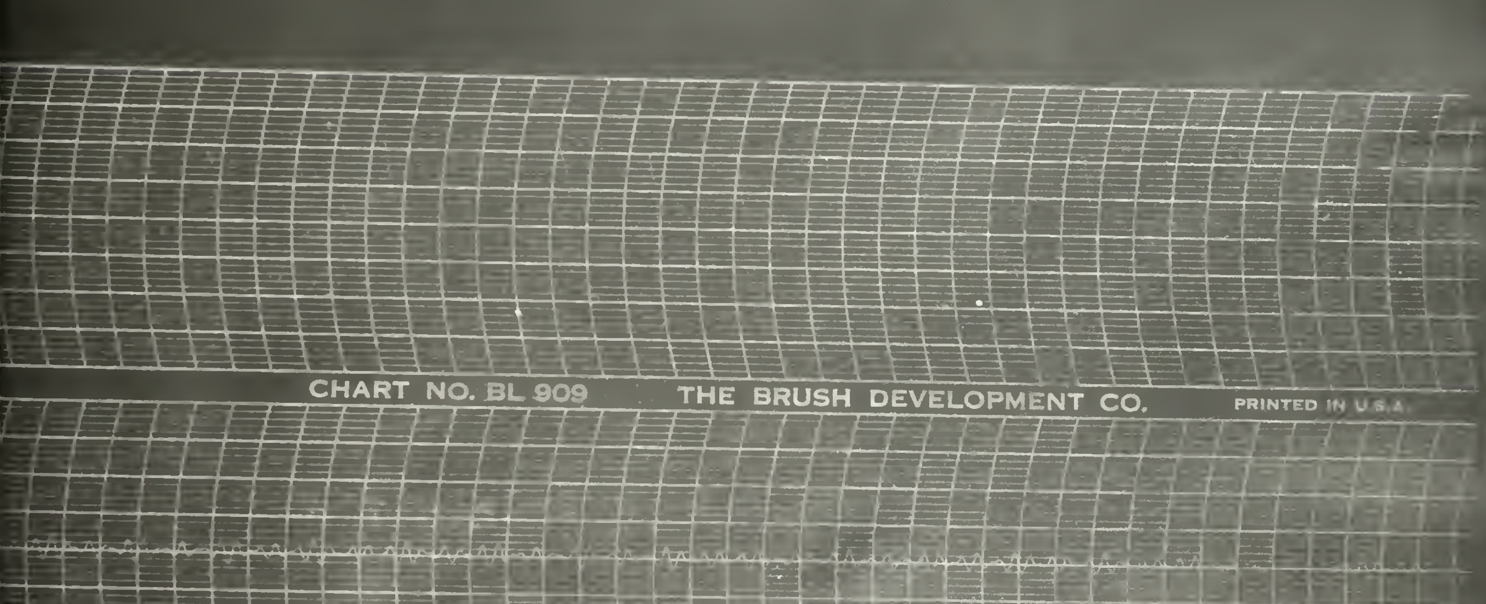
Run A5 3.869 cycles No feedback "Previous optimum" bias
Gain: 0.76 Phase shift: 81.54° lag



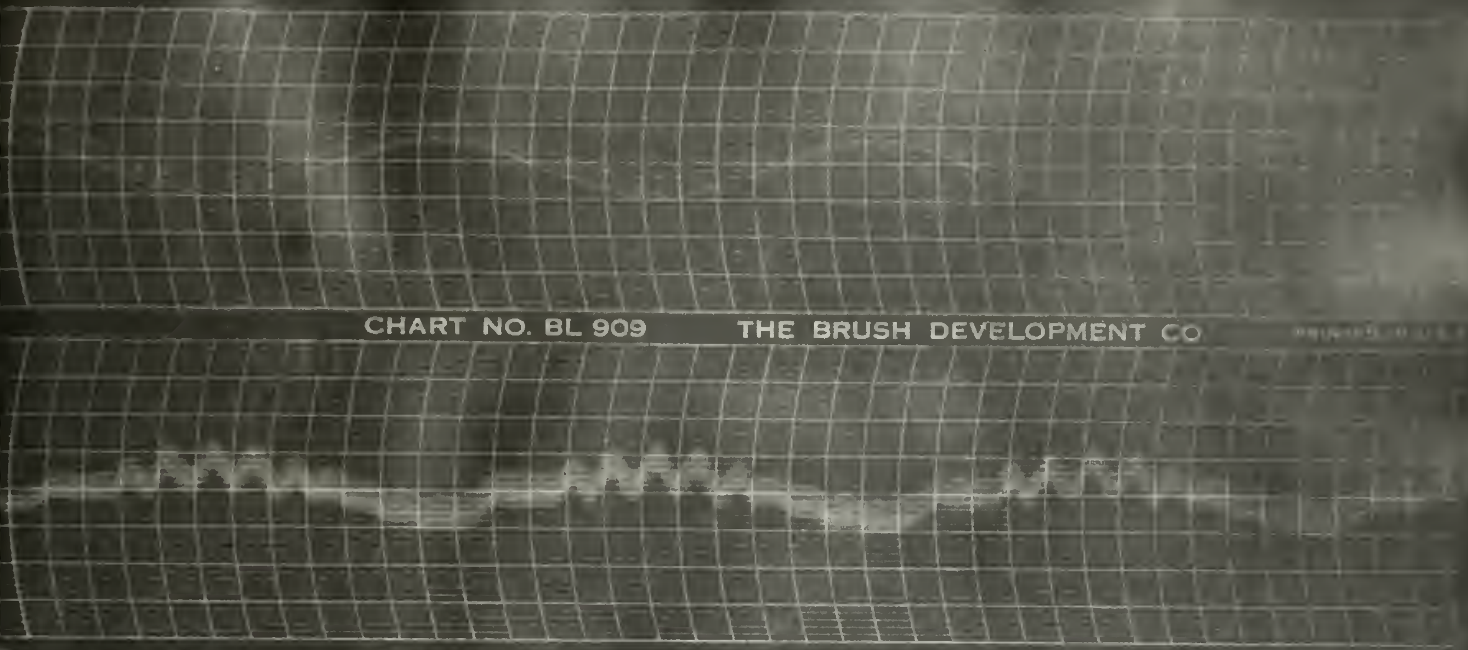
Run A6 5.078 cycles No feedback "Previous optimum" bias
Gain: 0.62 Phase shift: 106.99° lag



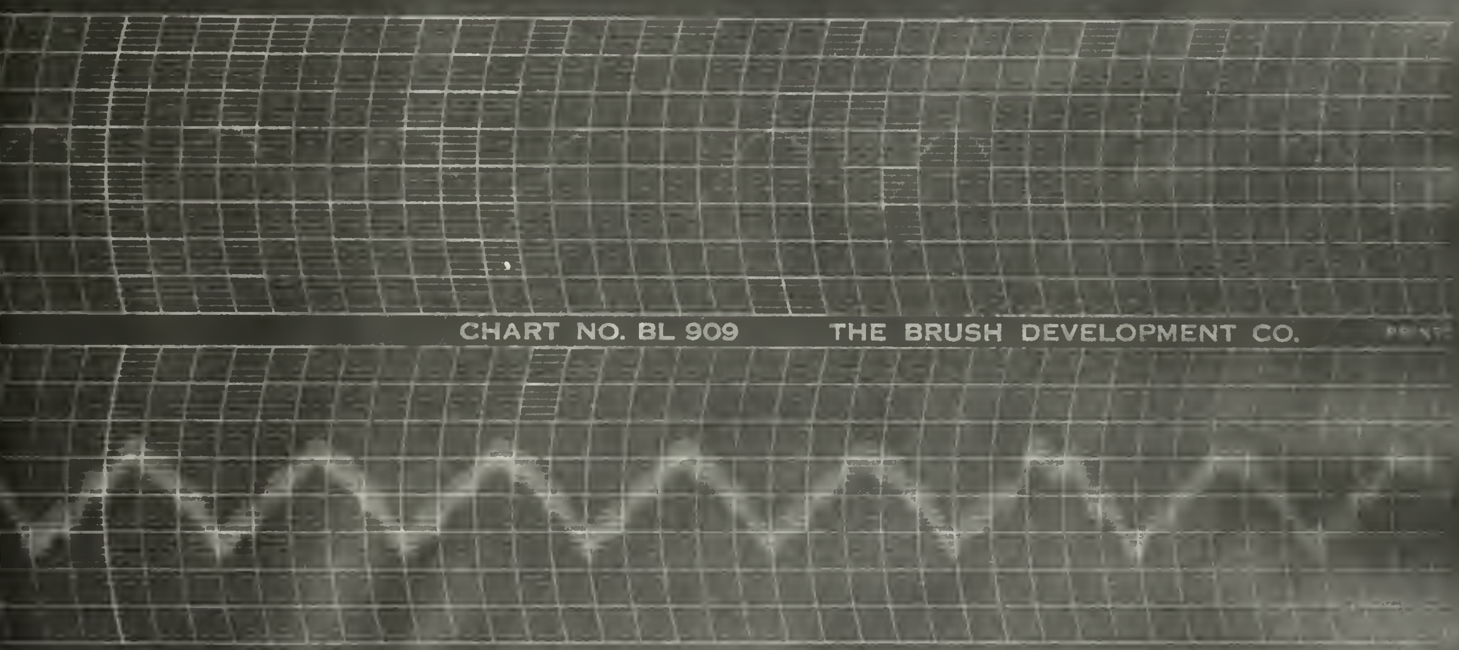
Run A7 6.818 cycles No feedback "Previous optimum" bias
Gain: 0.52 Phase shift: 128.73° lag



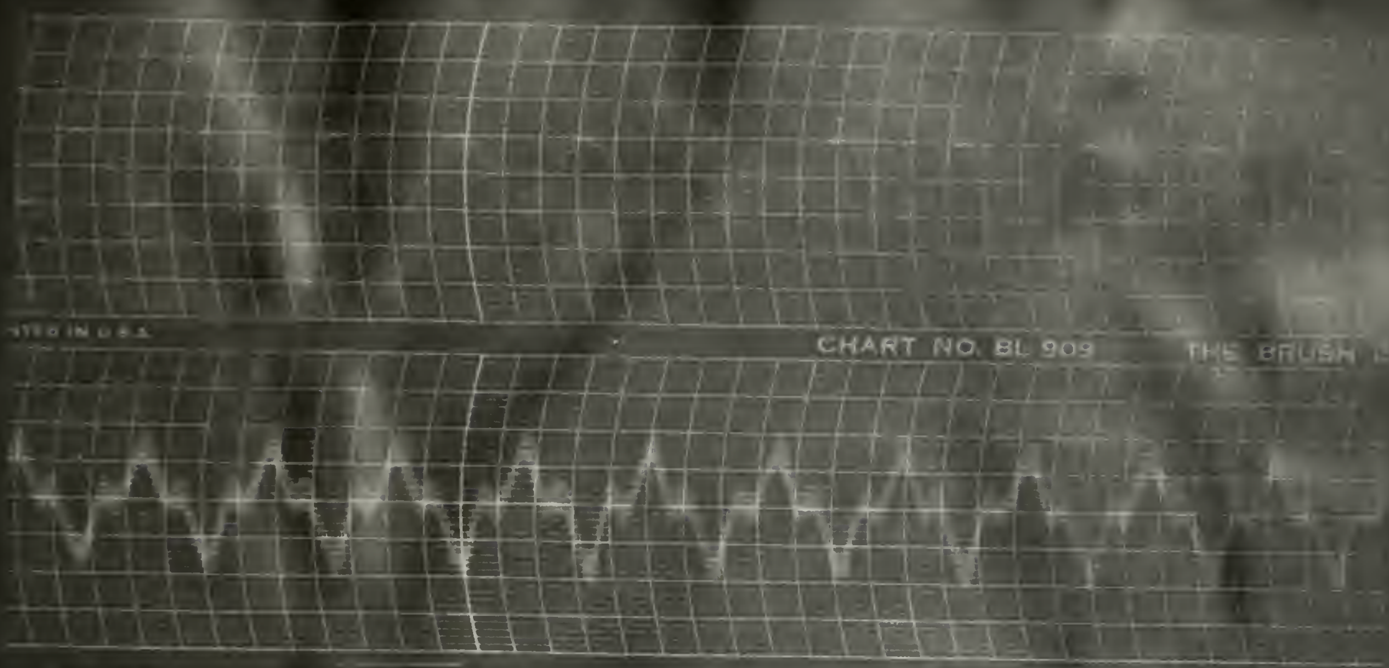
Run A8 8.338 cycles No feedback "Previous optimum" bias
Gain: 0.24 Phase shift: 135.08° lag



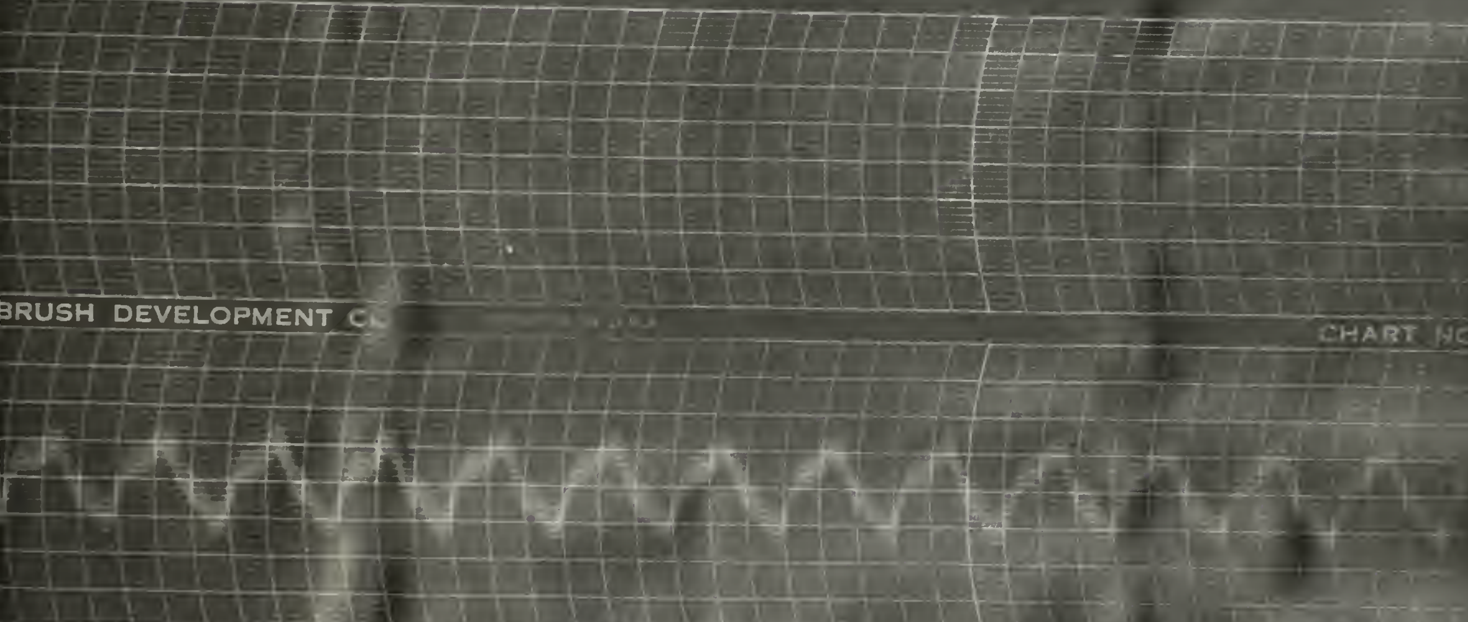
Run B1 o.419 cycles No feedback "Previous optimum" bias
Phase shift: 15.10° lag
Note: Resonance at approx. 4.53 cycles



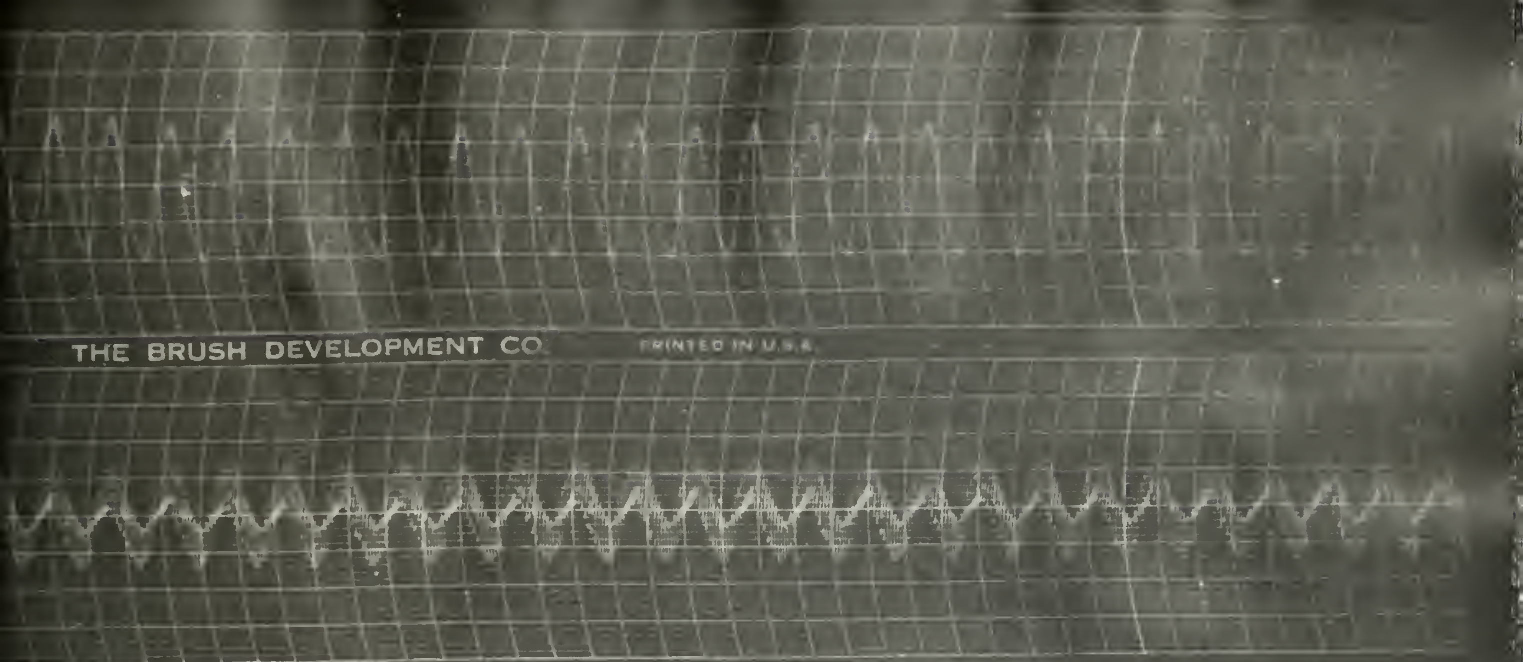
Run B2 1.010 cycles No feedback "Previous optimum" bias
Phase shift: 9.09° lead



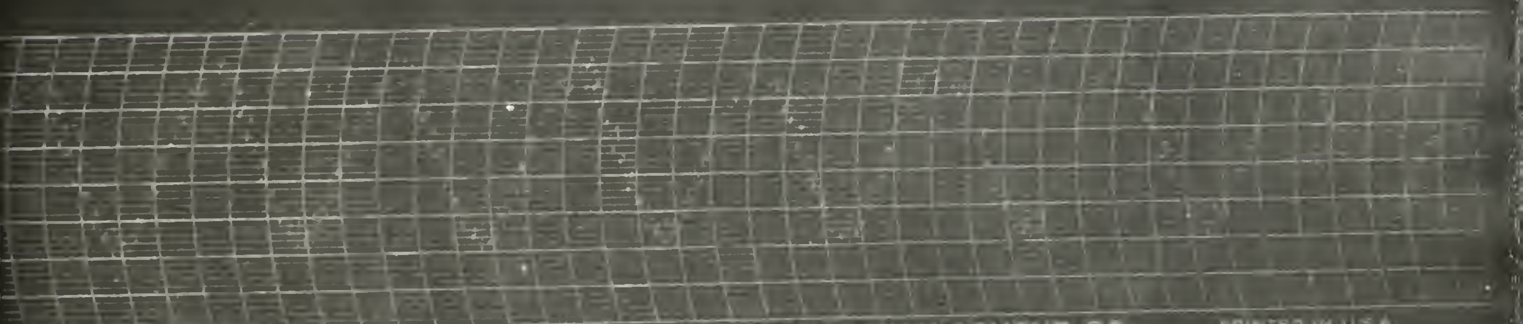
Run B3 1.478 cycles No feedback "Previous optimum" bias
Phase shift: 18.00° lag
Note: Resonance at approx. 4.43 cycles



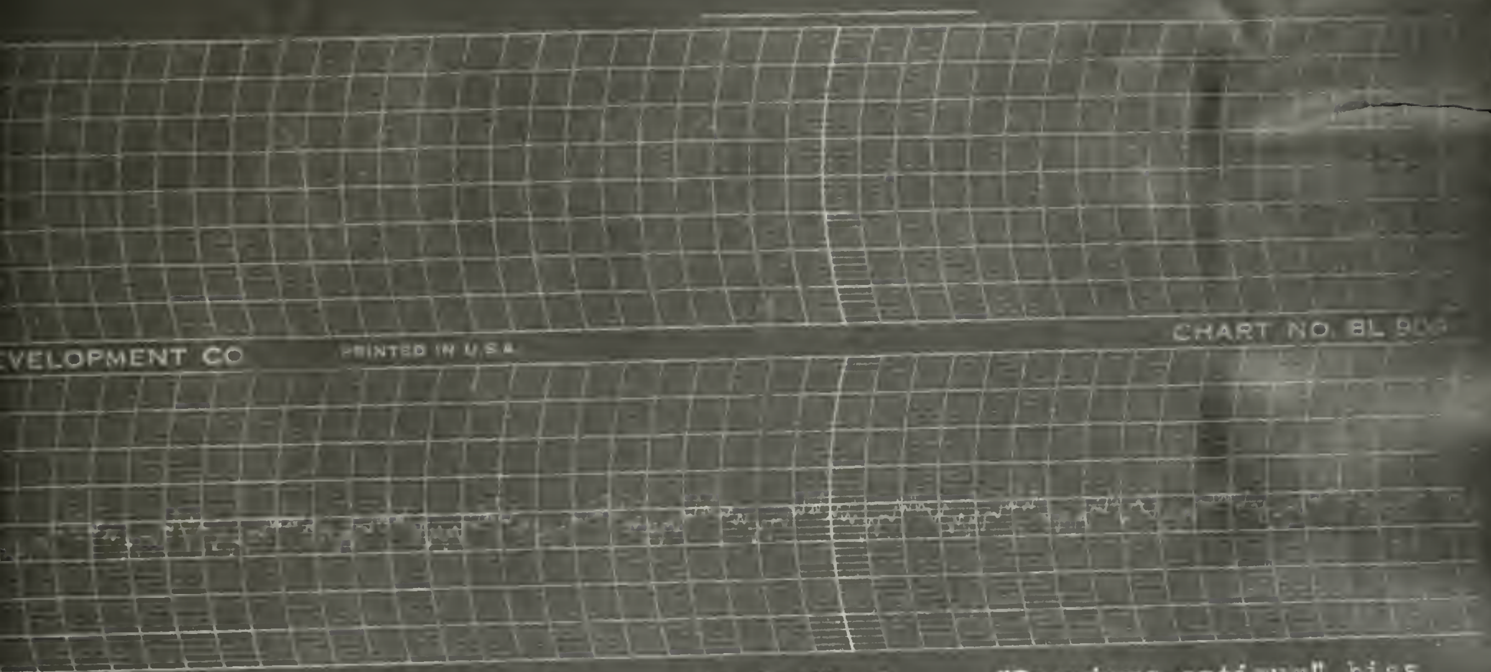
Run B4 1.668 cycles No feedback "Previous optimum" bias
Phase shift: 26.86° lag



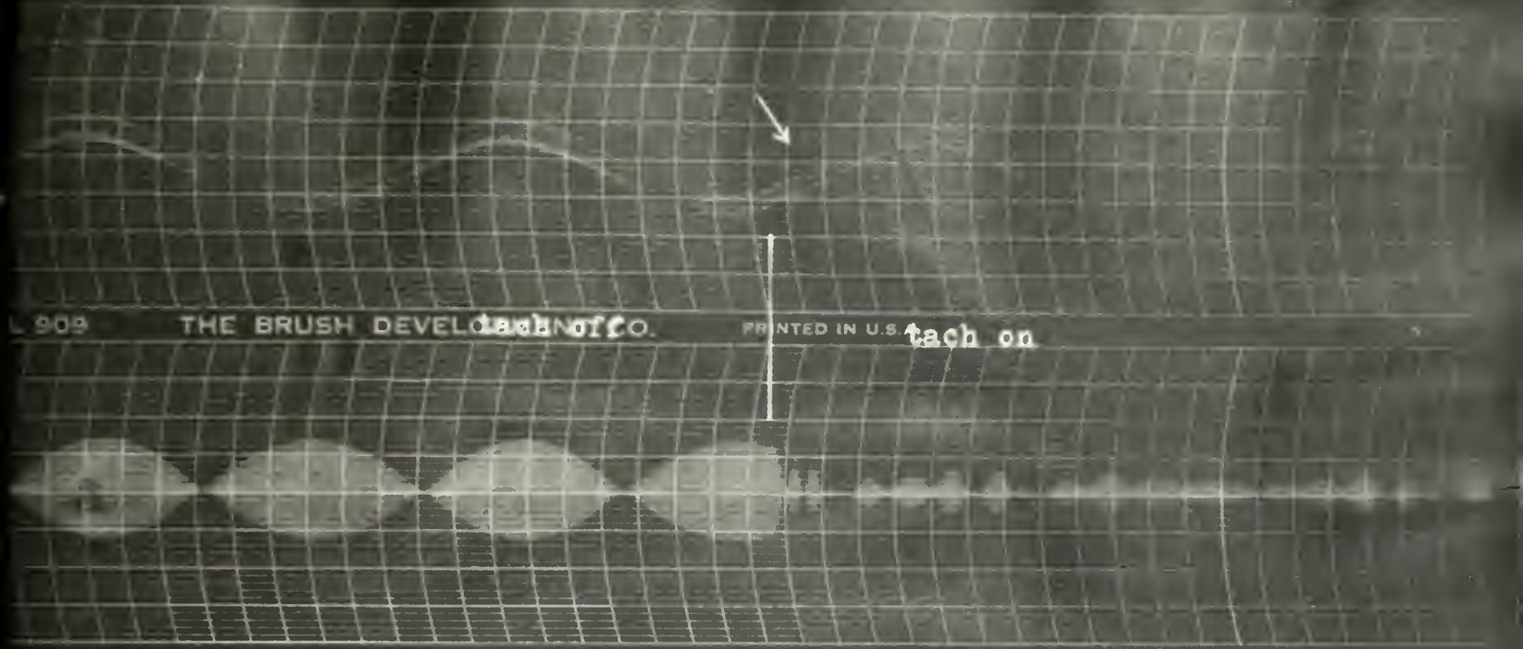
Run B5 3. 182 cycles No feedback "Previous optimum" bias
Phase shift: 133.8° (43.8°) lag



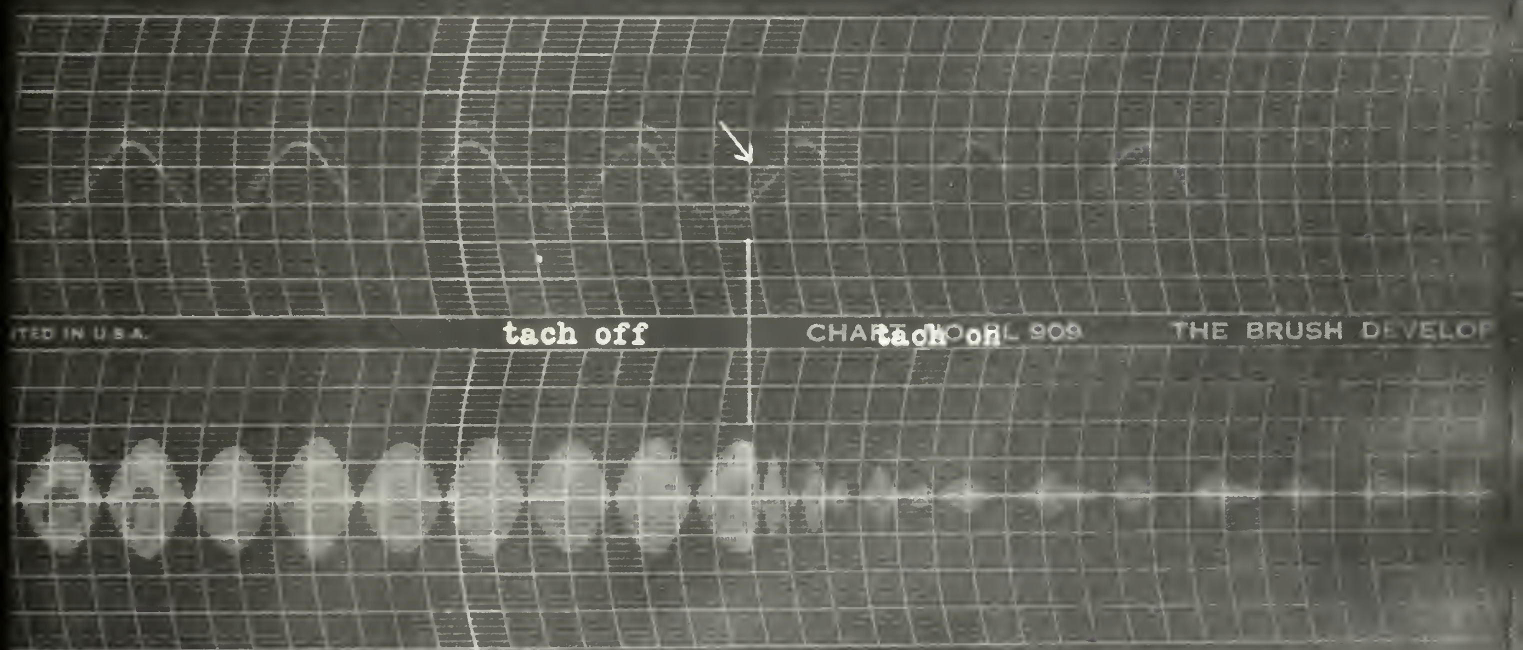
Run B6 5.050 cycles No feedback "Previous optimum" bias
Phase shift: 217.8° (127.8°) lag
Note: 120 cycle content



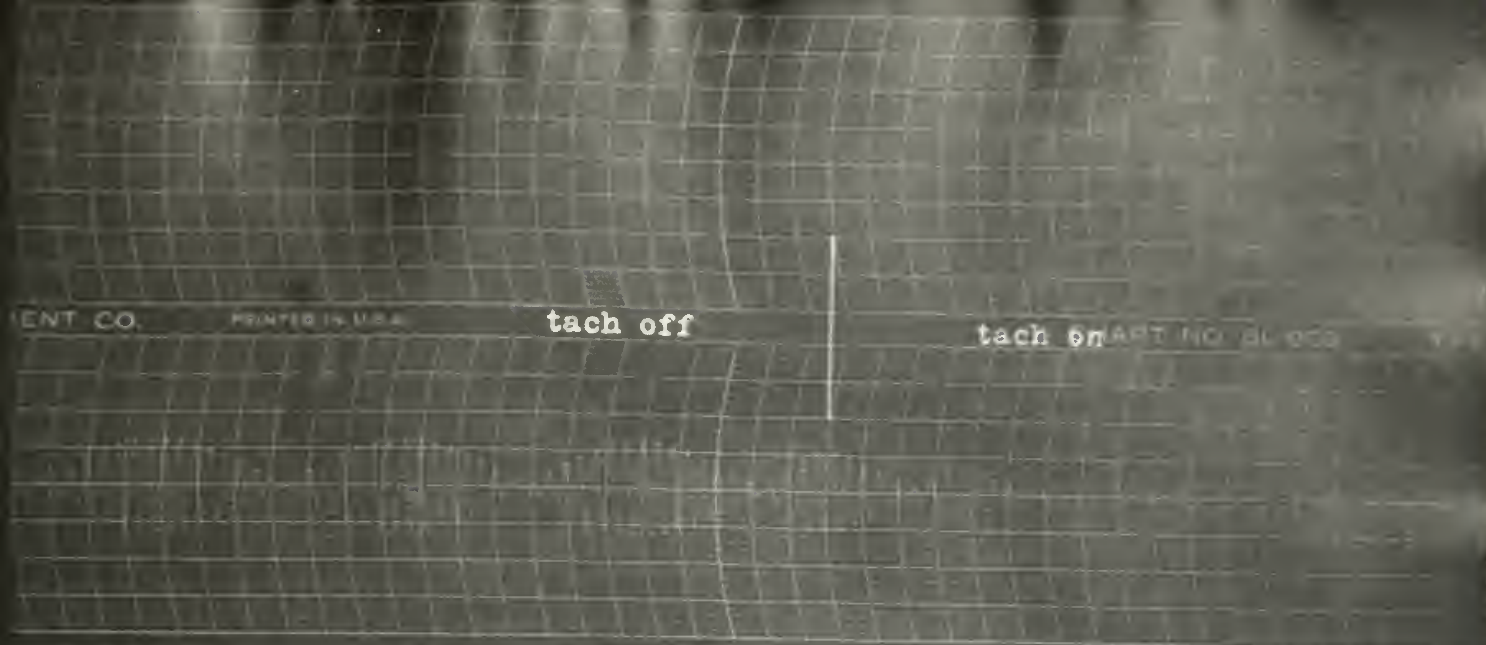
Run B7 8.835 cycles No feedback "Previous optimum" bias
Phase shift: 153.54° (63.54°) lag



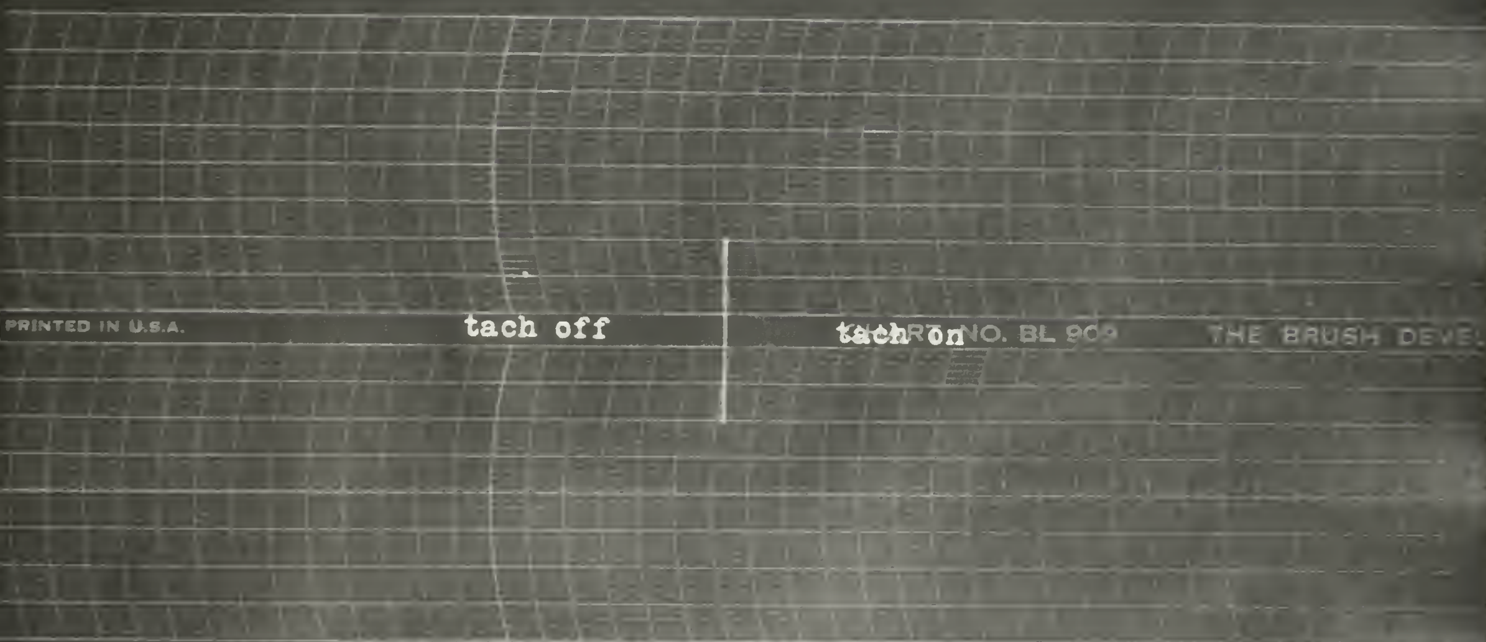
Run C1 o.437 cycles No feedback "Previous optimum" bias
Response reduced, but bears no relation to input
Note: Feedback to input circuit when tach loop is closed



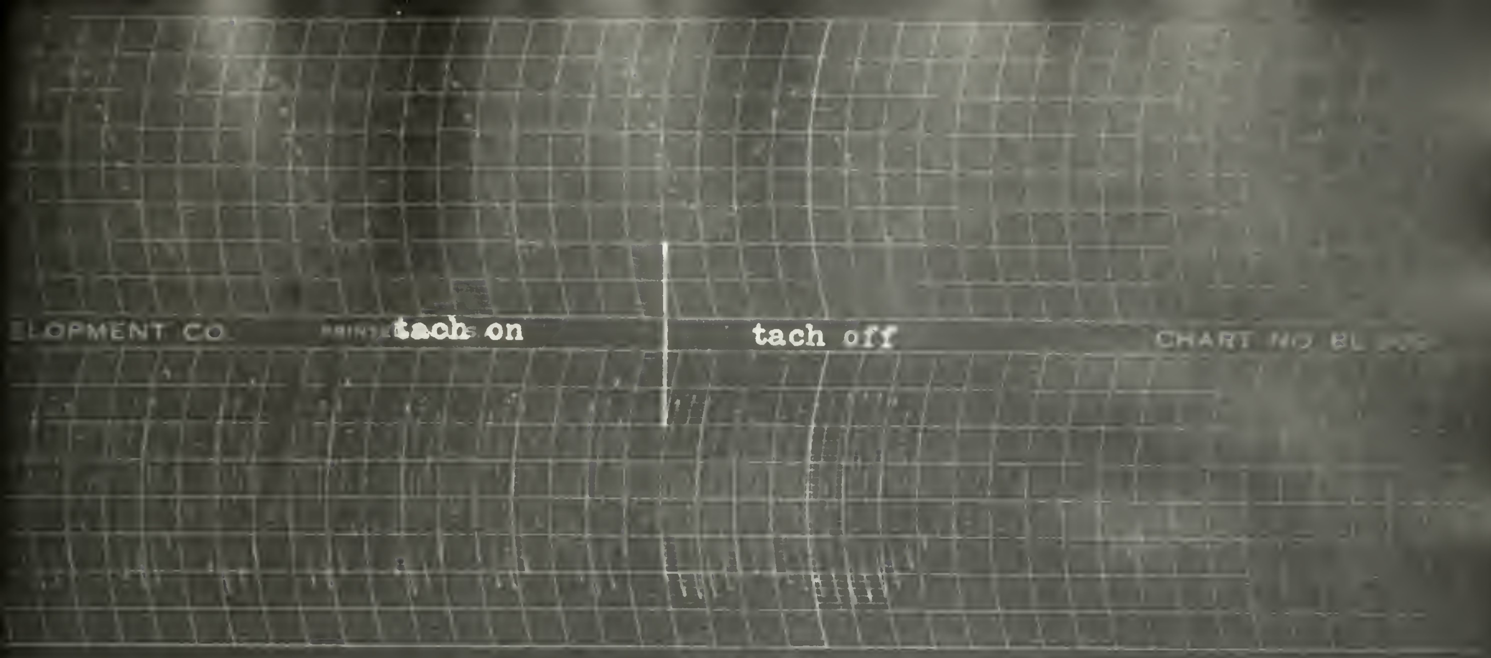
Run C2 1.084 cycles No feedback "Previous optimum" bias
Response reduced, but badly distorted



Run C3 1.911 cycles No feedback "Previous optimum" bias
Response reduced, but less distorted than at 1.084 cycles

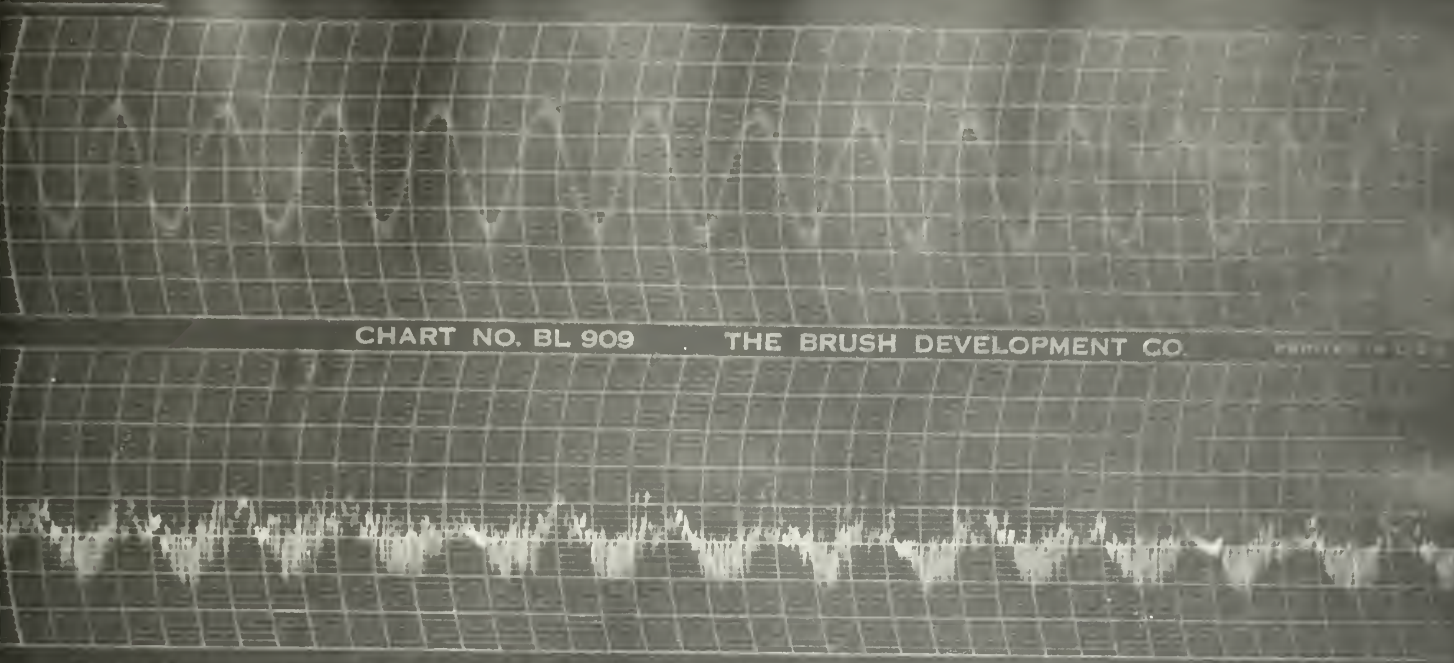


Run C4 3.833 cycles No feedback "Previous optimum" bias
Response increased, but not distorted

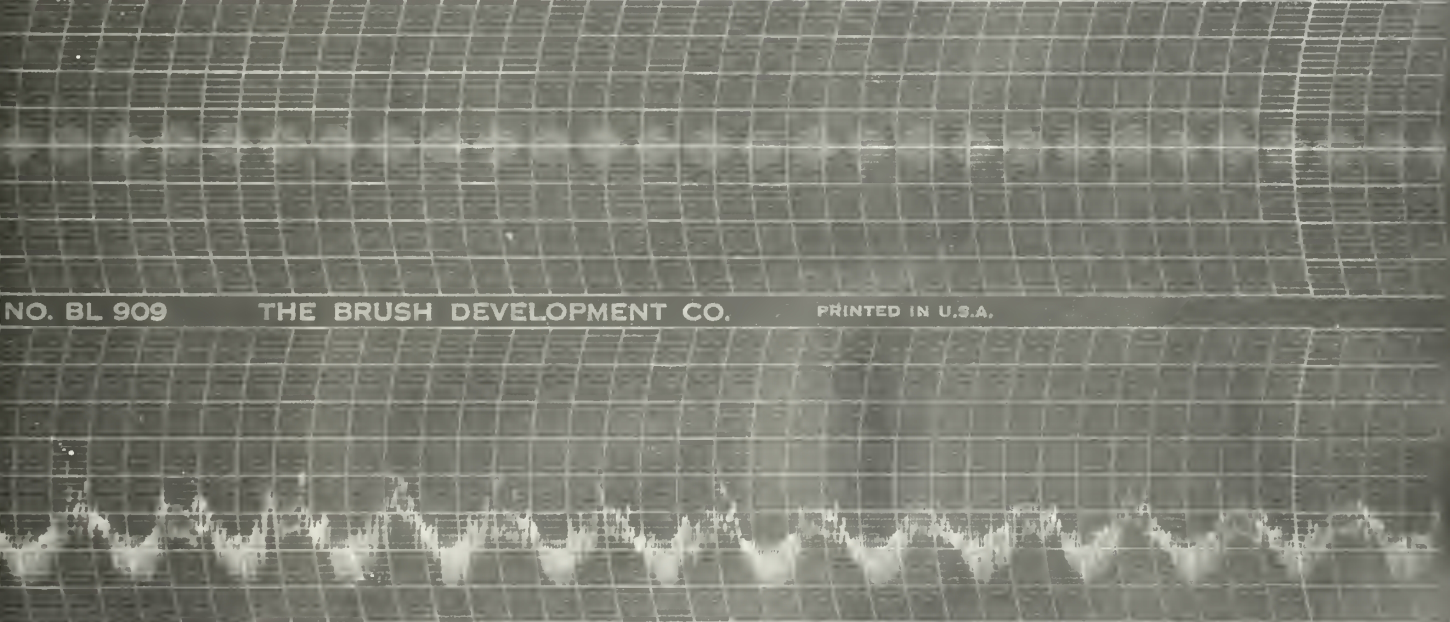


Run C5 5.088 cycles No feedback "Previous optimum" bias
Response increased greatly.
Note: 120 cycle component

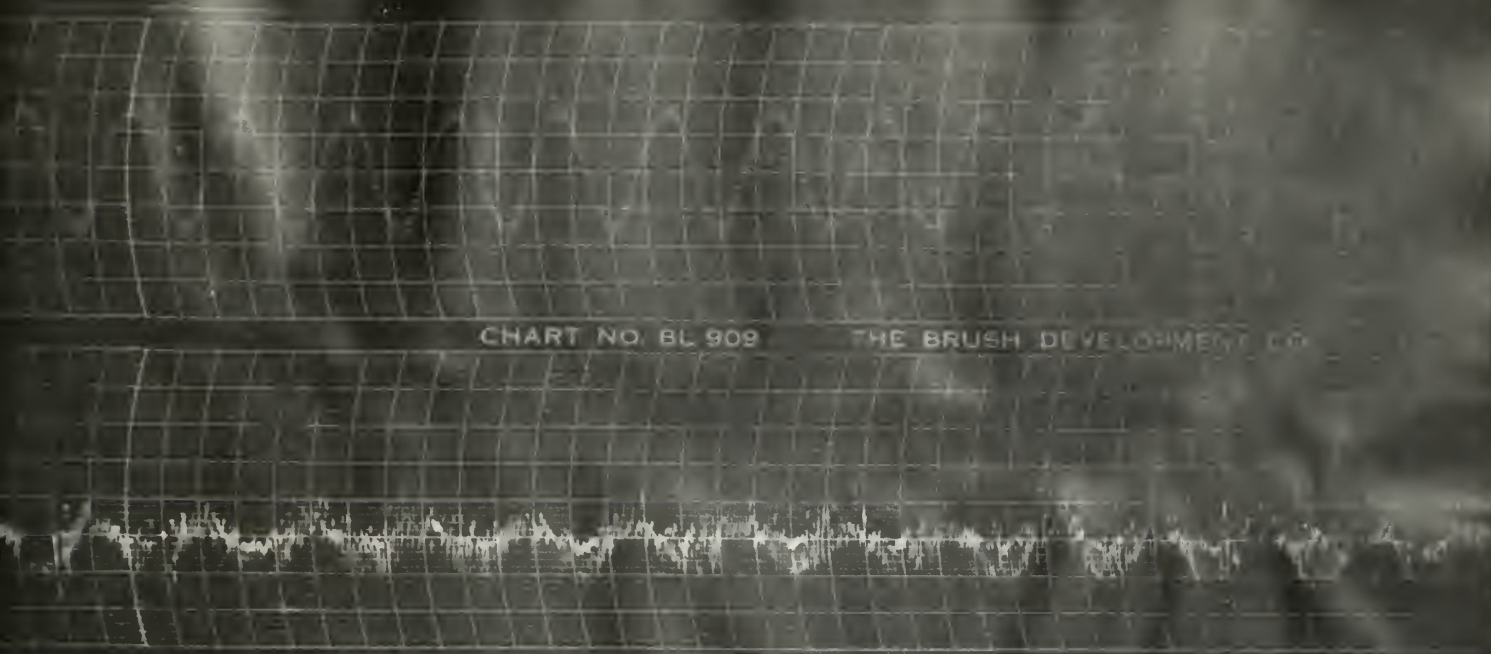
Run C6 8.88 cycles No feedback "Previous optimum" bias
Response increased, also have an approx. 4.05 cycle component



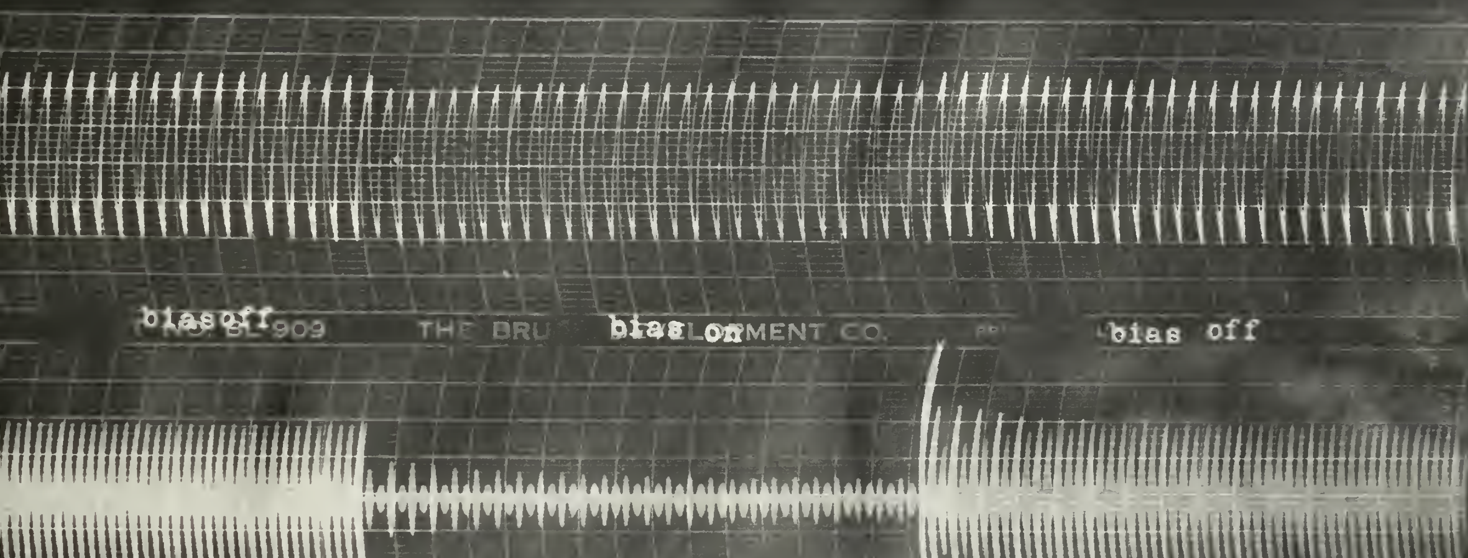
Run D1 1.728 cycles No feedback
Z_3Z_4 vs input



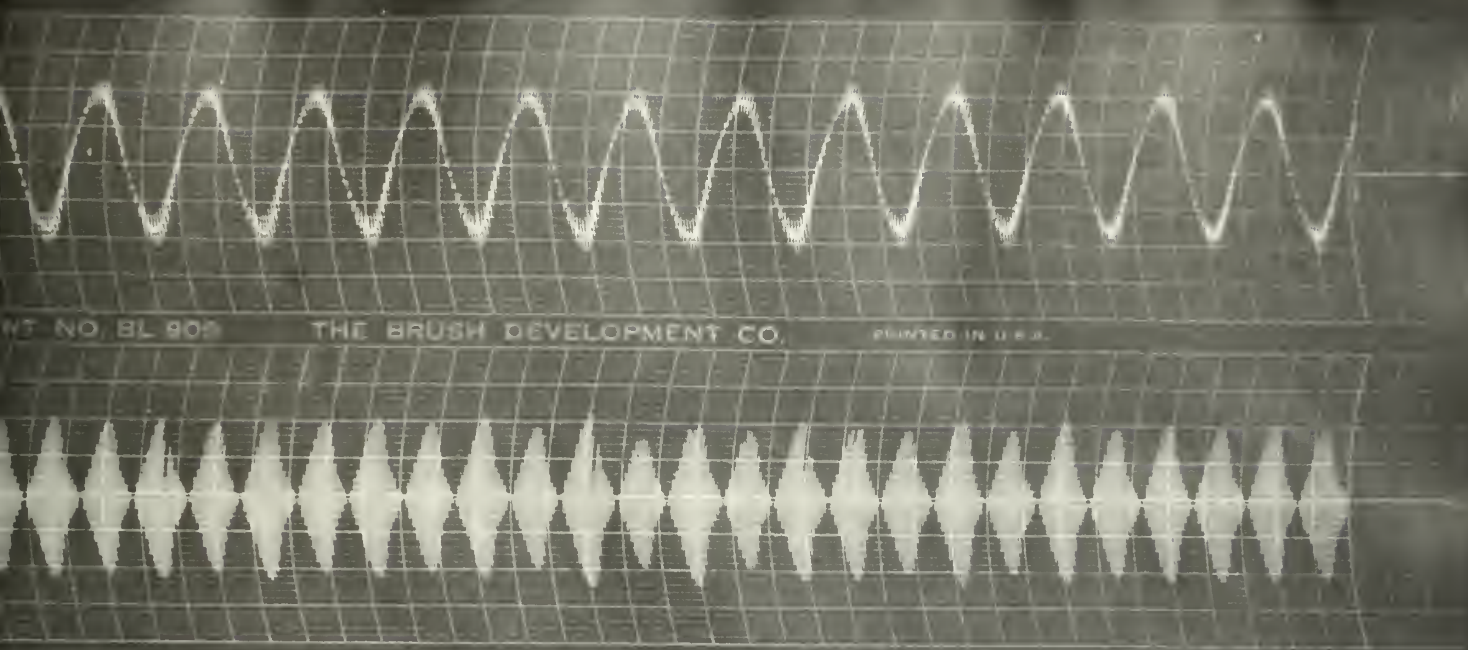
Run D2 1.728 cycles No feedback
Z_3Z_4 vs output



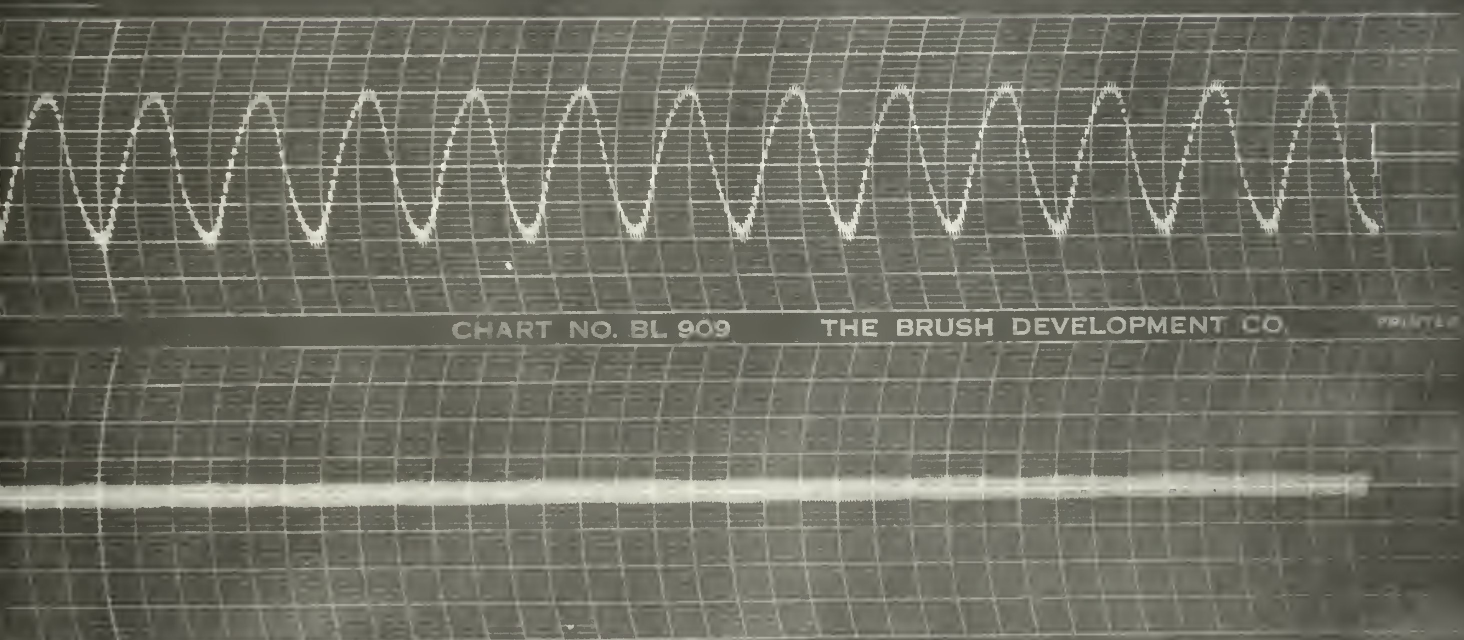
Run D3 1.728 cycles No feedback
Y_3Y_4 vs input



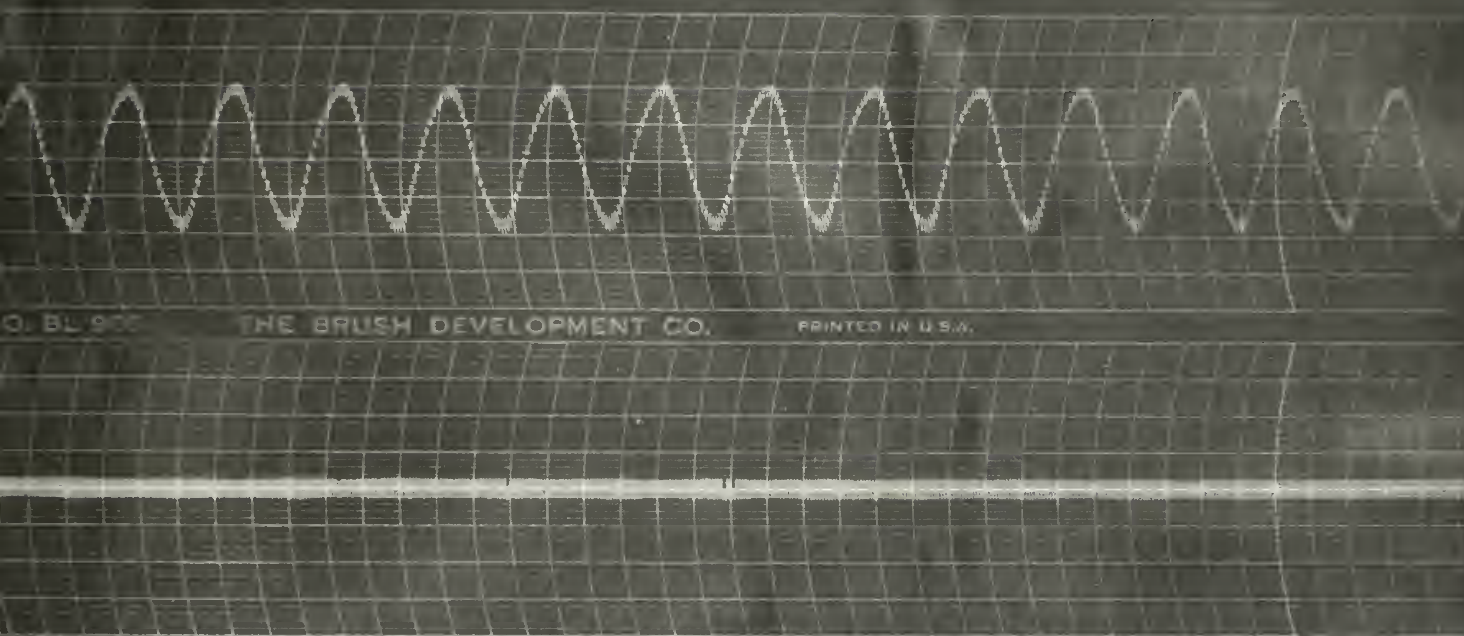
Run D4 1.728 cycles No feedback Output with
maximum and no bias
Note: Slow (8 second) trandient response when bias
circuit is opened and closed



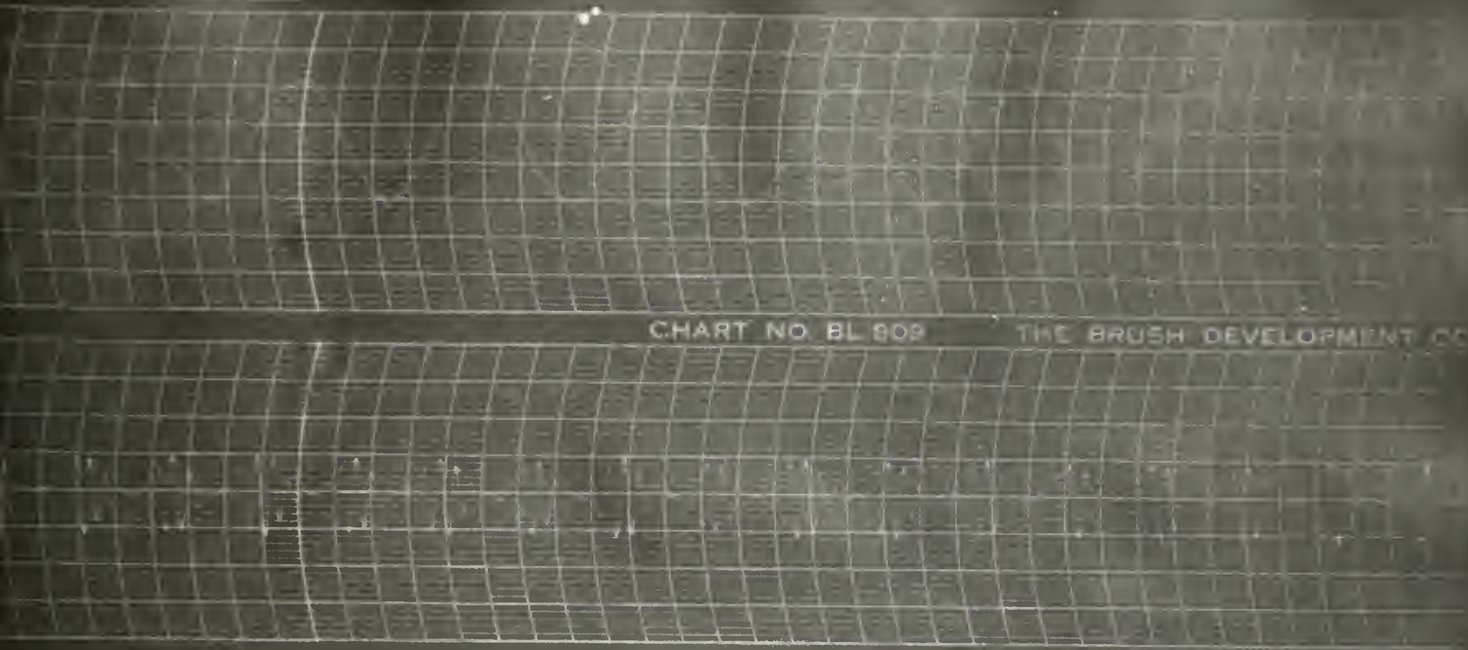
Run D5 1.728 cycles No feedback No bias



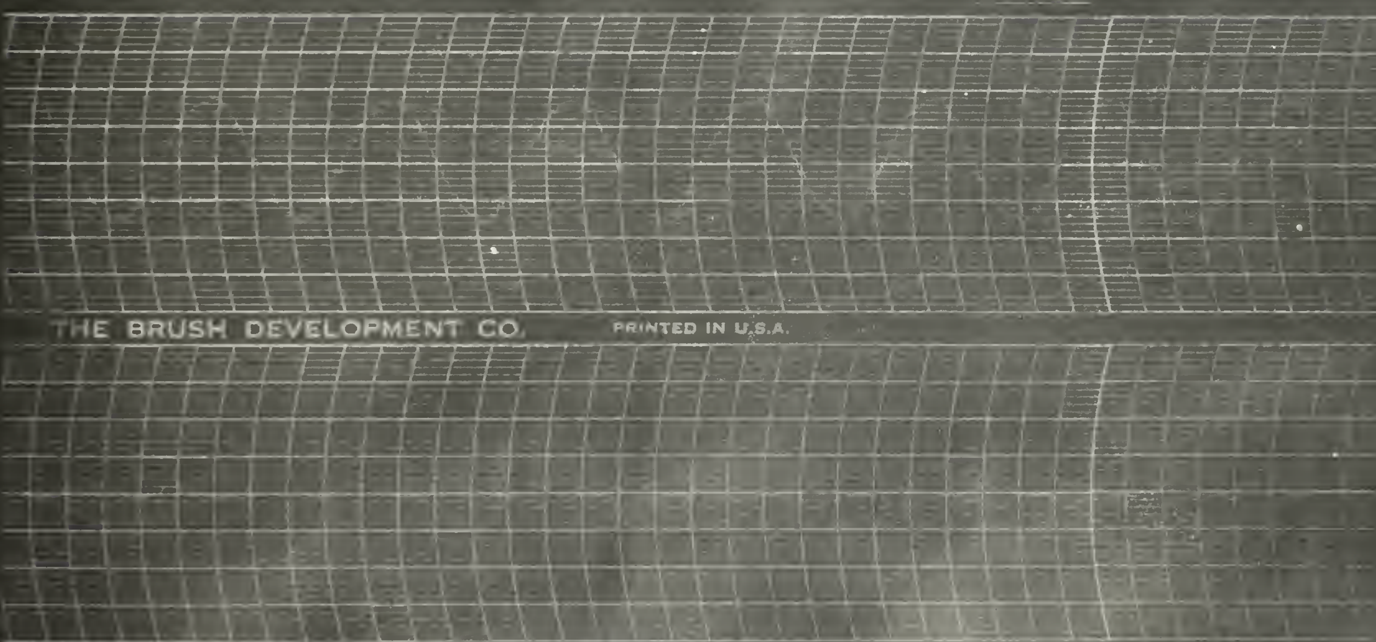
Run D6 1.728 cycles With feedback No bias



Run D7 1.728 cycles With feedback "Previous optimum" bias

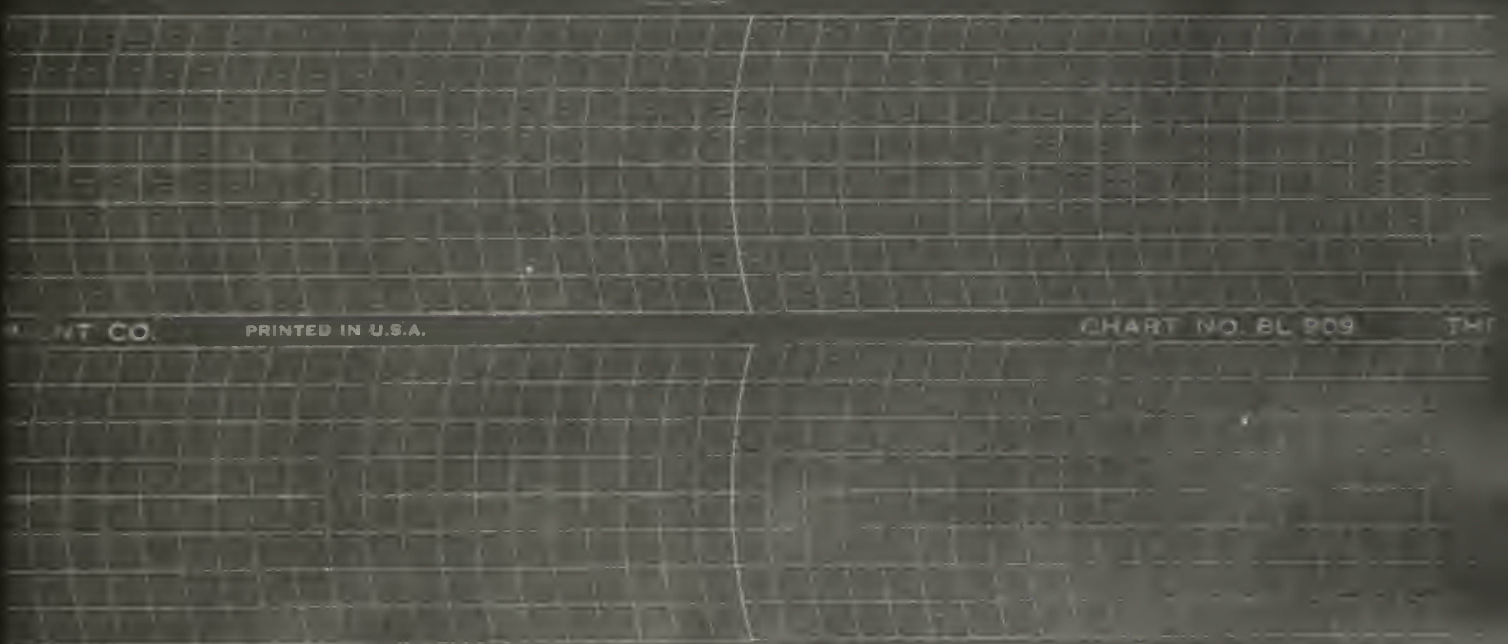


Run E1 5.062 cycles No feedback No bias



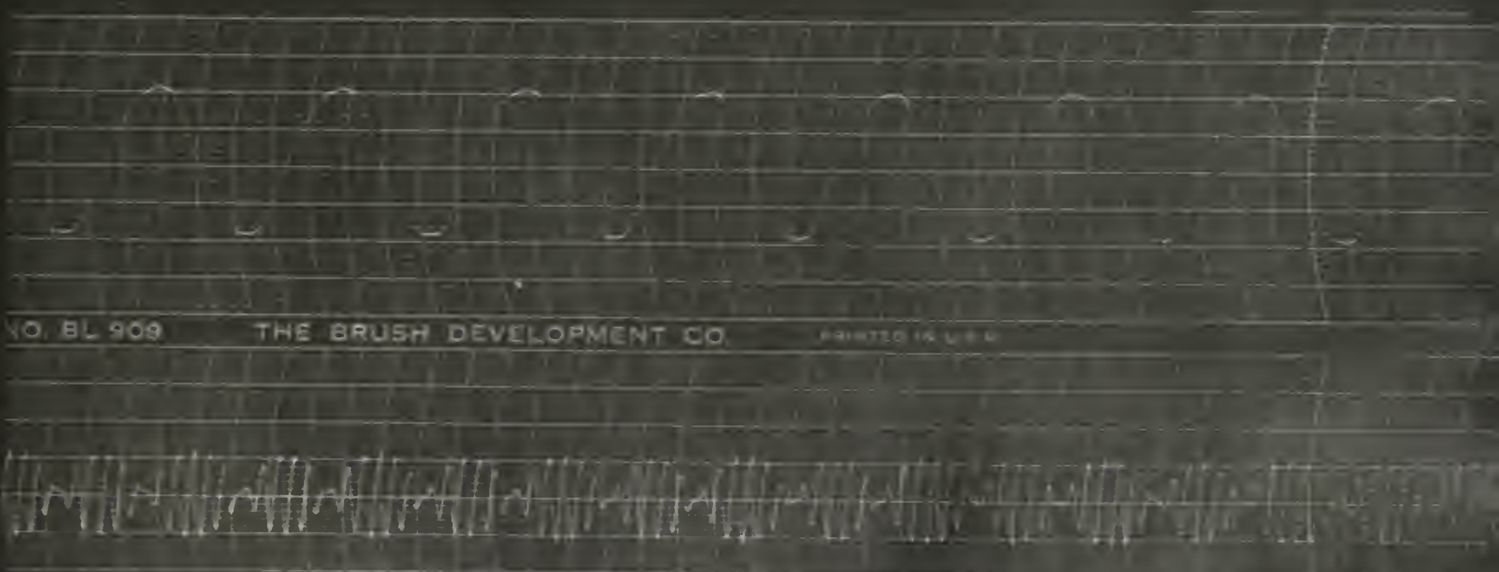
Run E2 5.062 cycles Reversed parallel feedback No bias

Run E3 5.062 cycles Reversed parallel feedback
"Previous optimum" bias

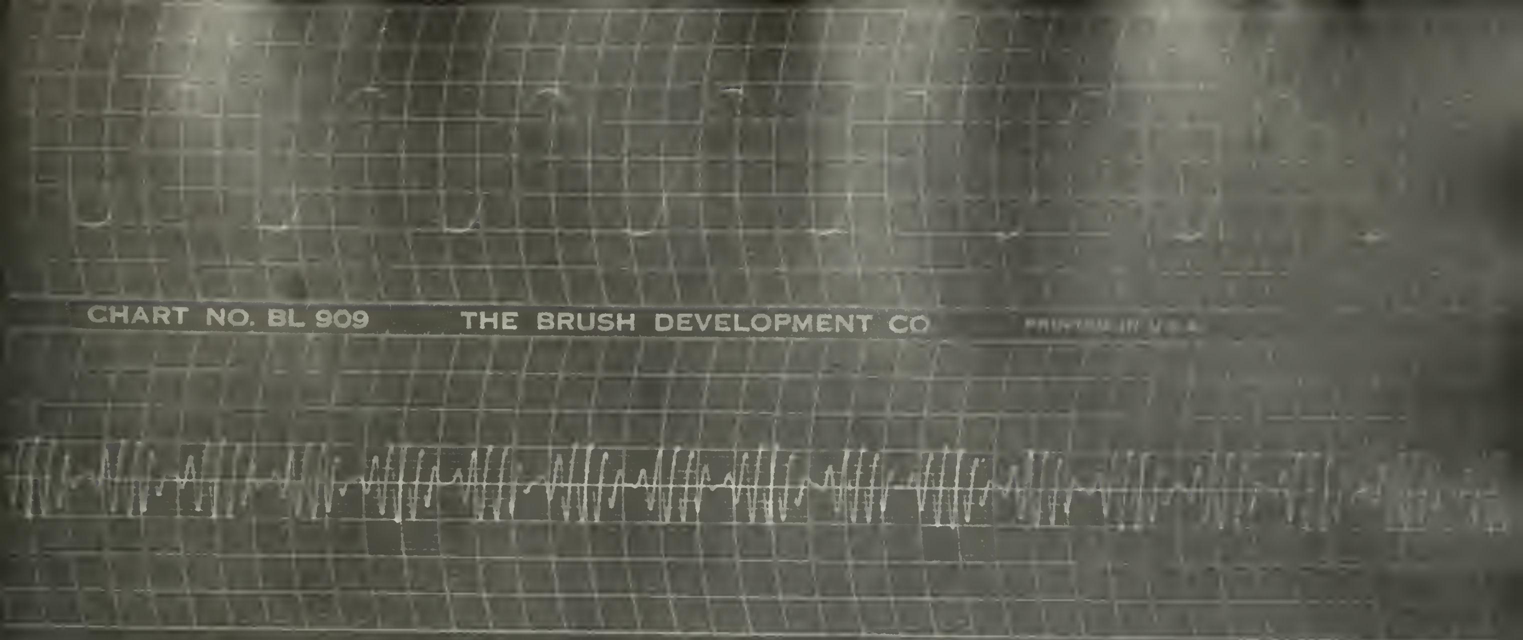


Run E4 5.062 cycles Crisscross feedback No bias

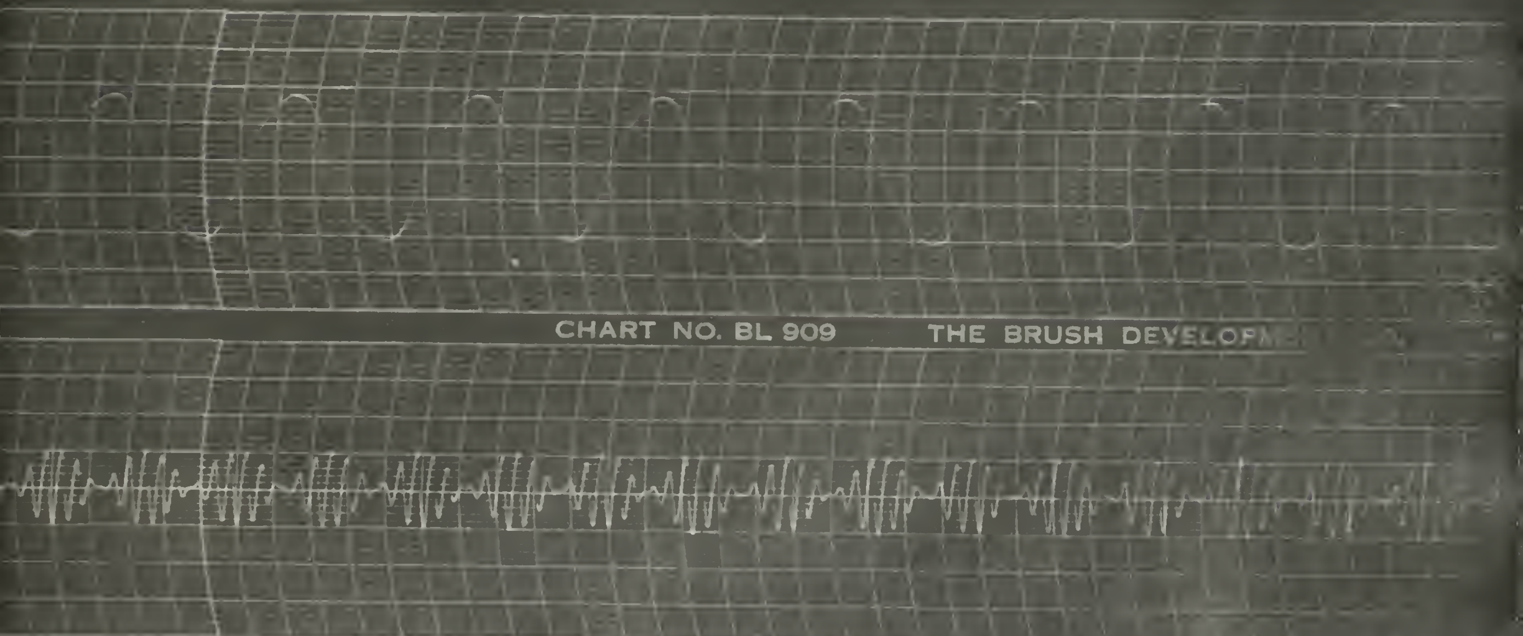
Run F1 5.070 cycles No feedback No bias
Gain: 1.00 (reference) Phase shift: 89.9° lag



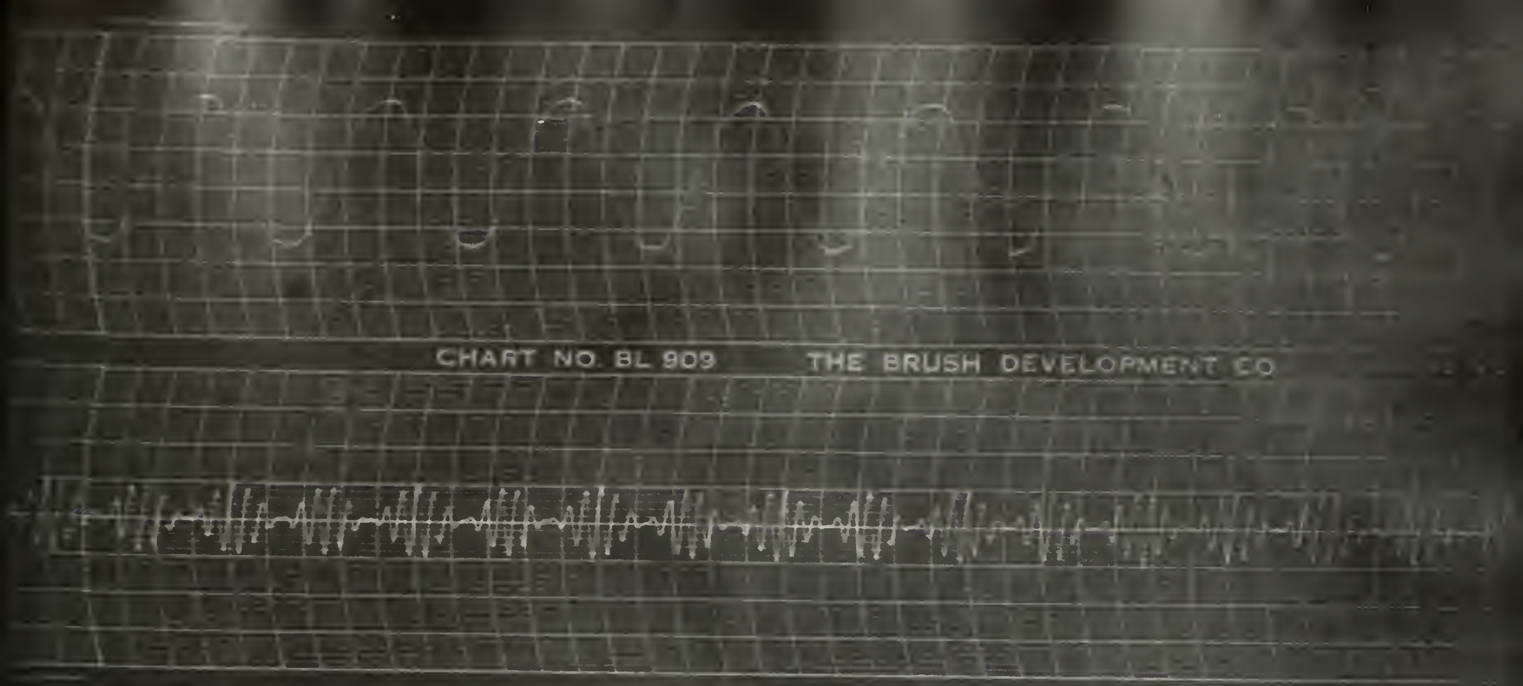
Run F2 5.070 cycles No feedback Bias: pt. 1 (minimum)
Gain: 1.89 Phase shift: 8[illegible].1° lag



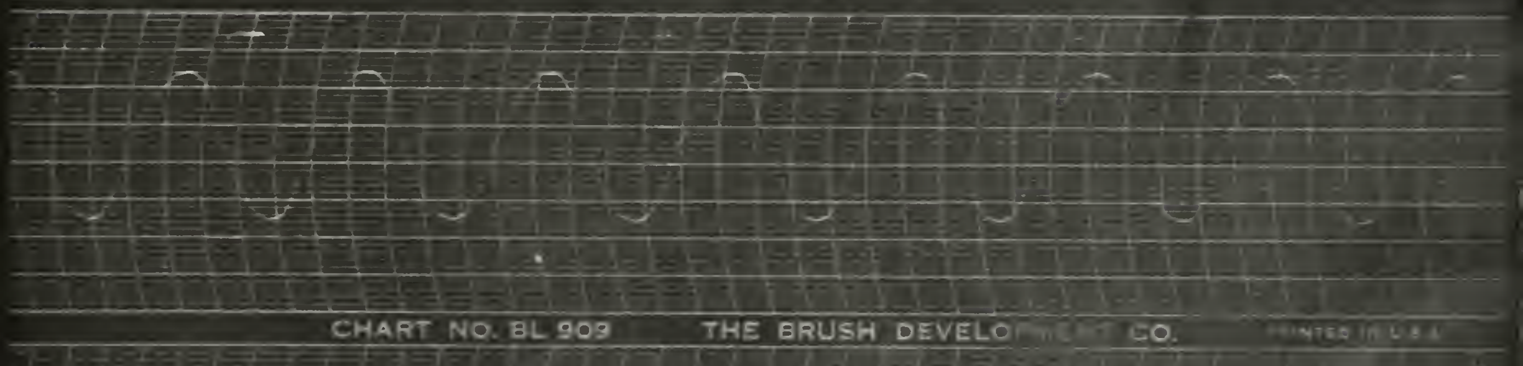
Run F3   5.070 cycles   No feedback   Bias: pt. 2
Gain: 1.82   Phase shift: 83.8° lag



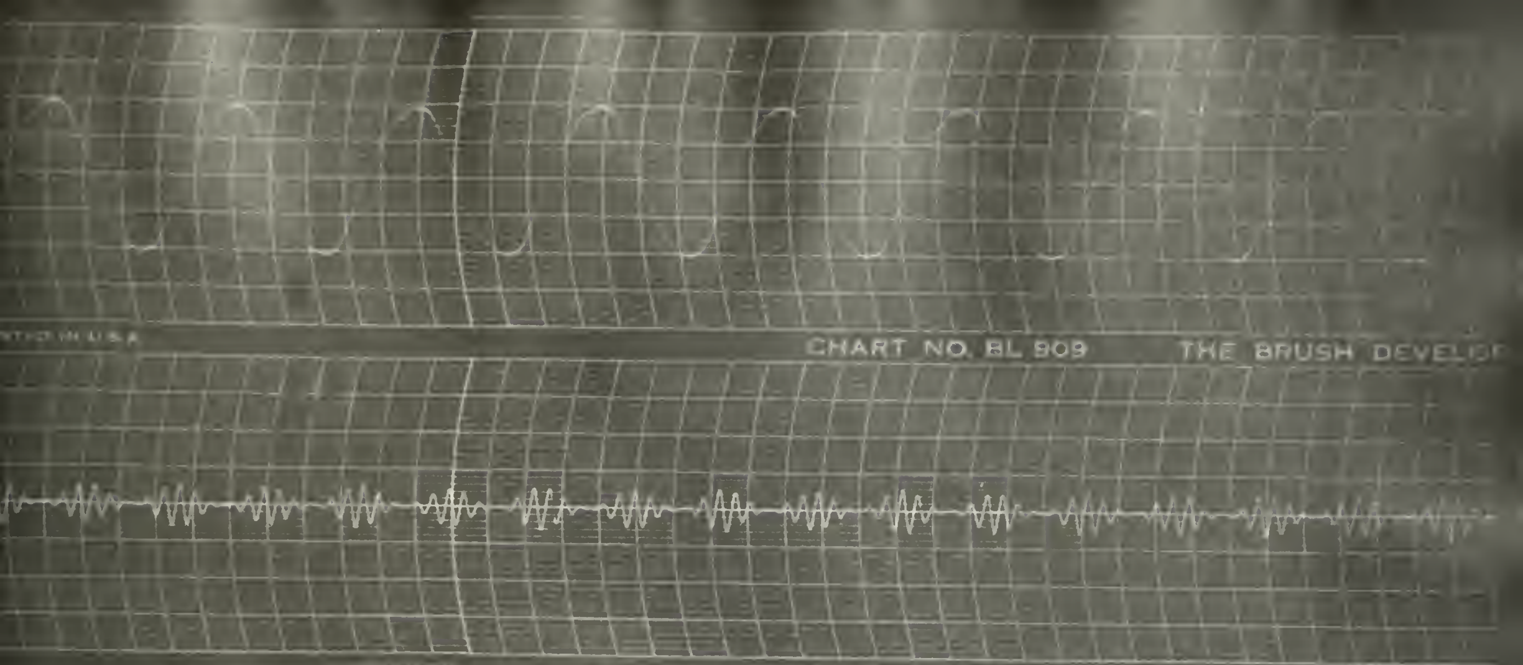
Run F4   5.070 cycles   No feedback   Bias: pt. 3
Gain: 1.78   Phase shift: 79.8° lag



Run F5 5.070 cycles No feedback Bias: pt. 4
Gain: 1.62 Phase shift: 80.6° lag

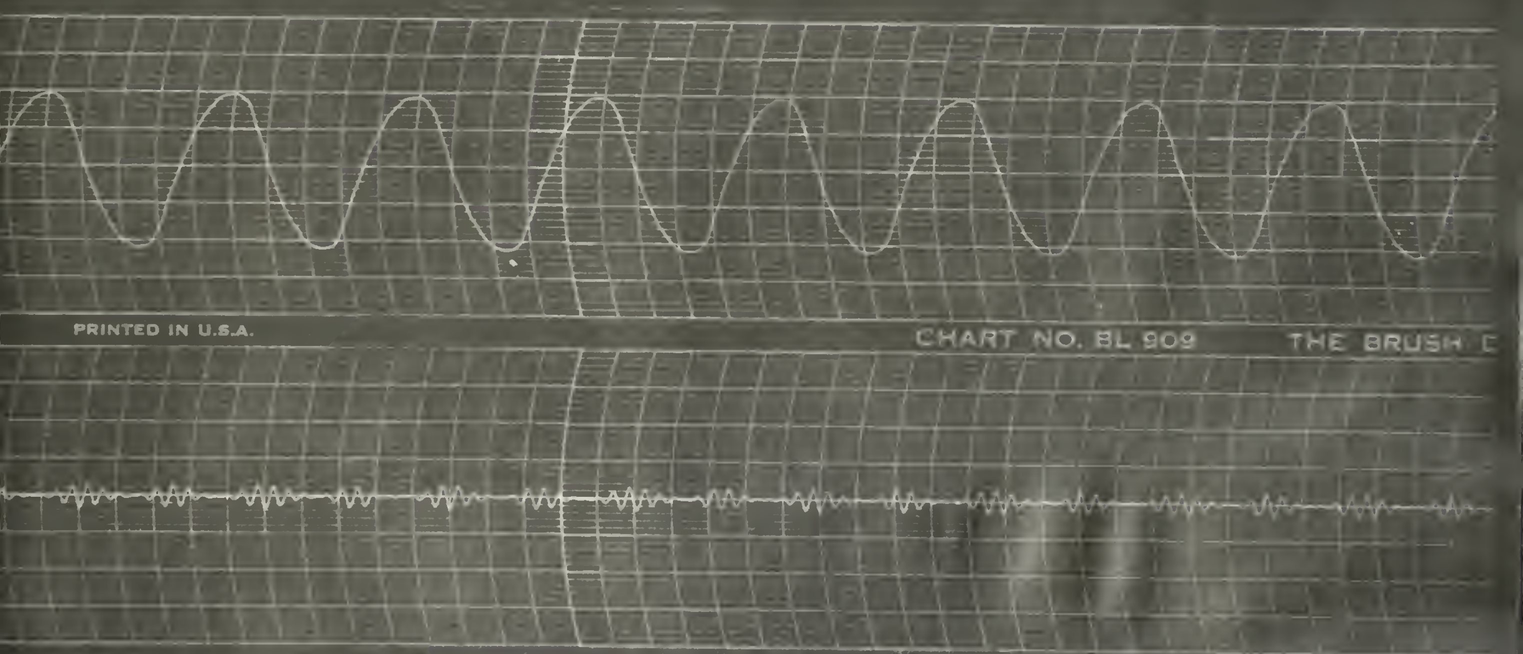


Run F6 5.070 cycles No feedback Bias: pt. 5
Gain: 1.24 Phase shift: 85.2° lag



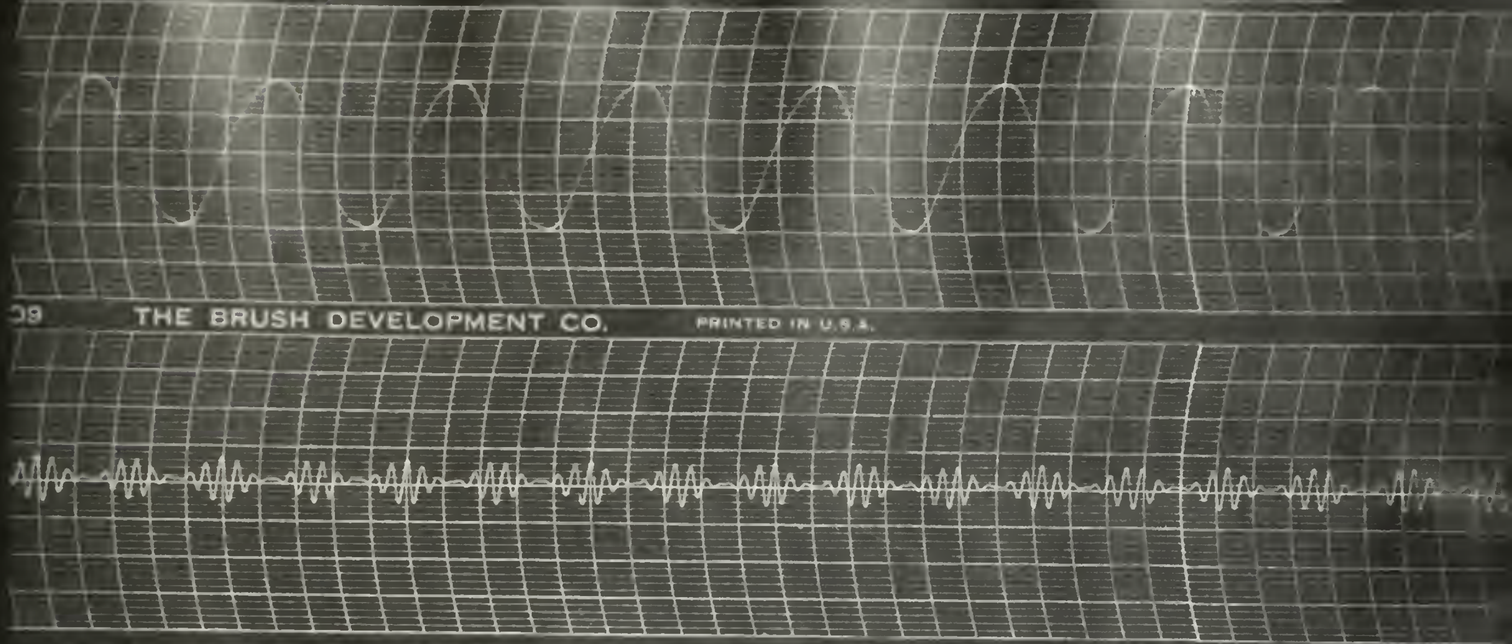
Run F7   5.070 cycles   No feedback   Bias: pt. 6, "Previous optimum"

Gain: o.95   Phase shift: 80.6° lag

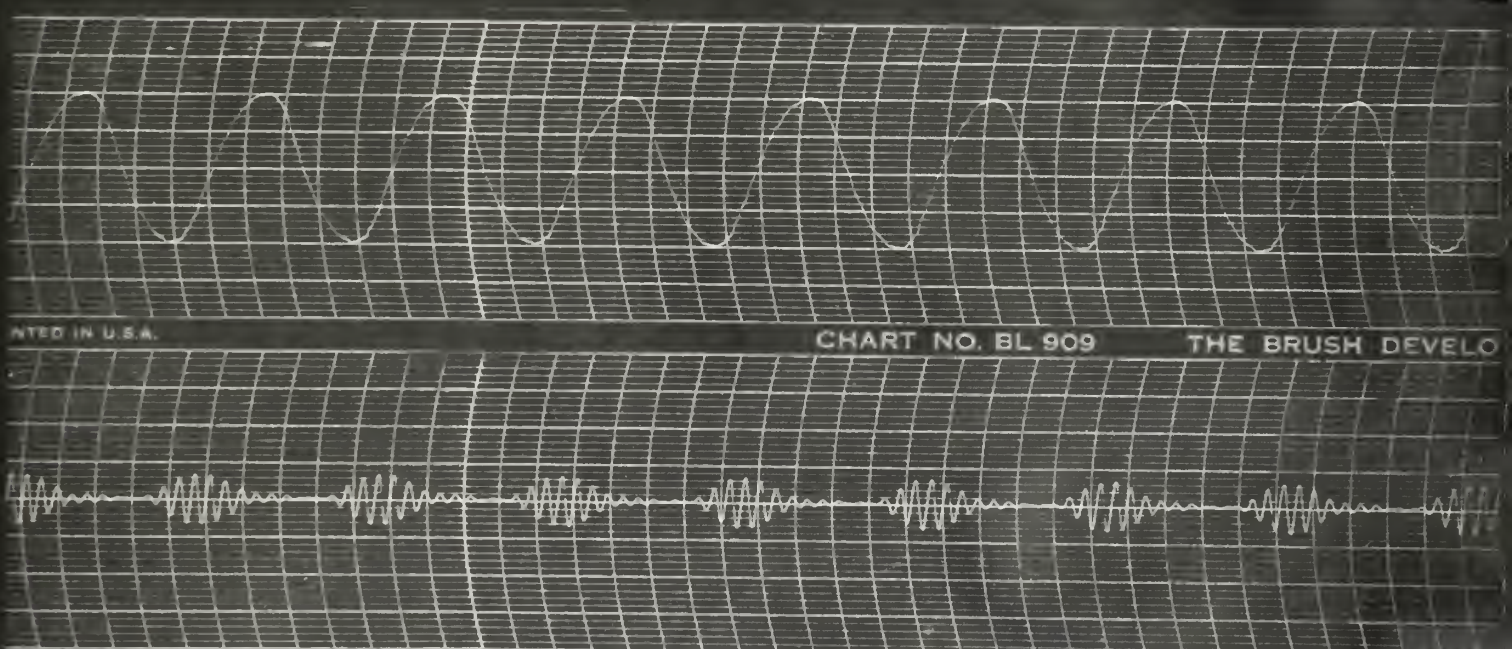


Run F8   5.070 cycles   No feedback   Bias: pt. 7

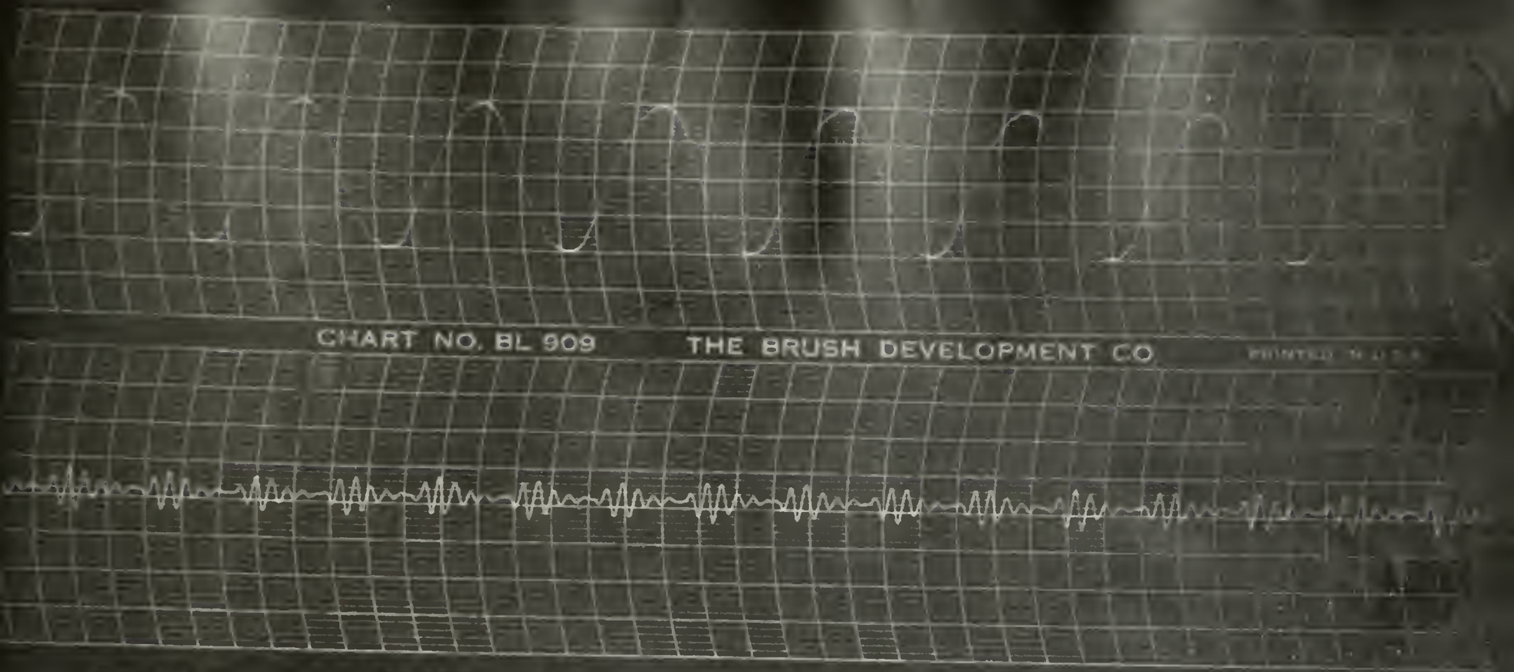
Gain: 0.53   Phase shift: 82.08° lag



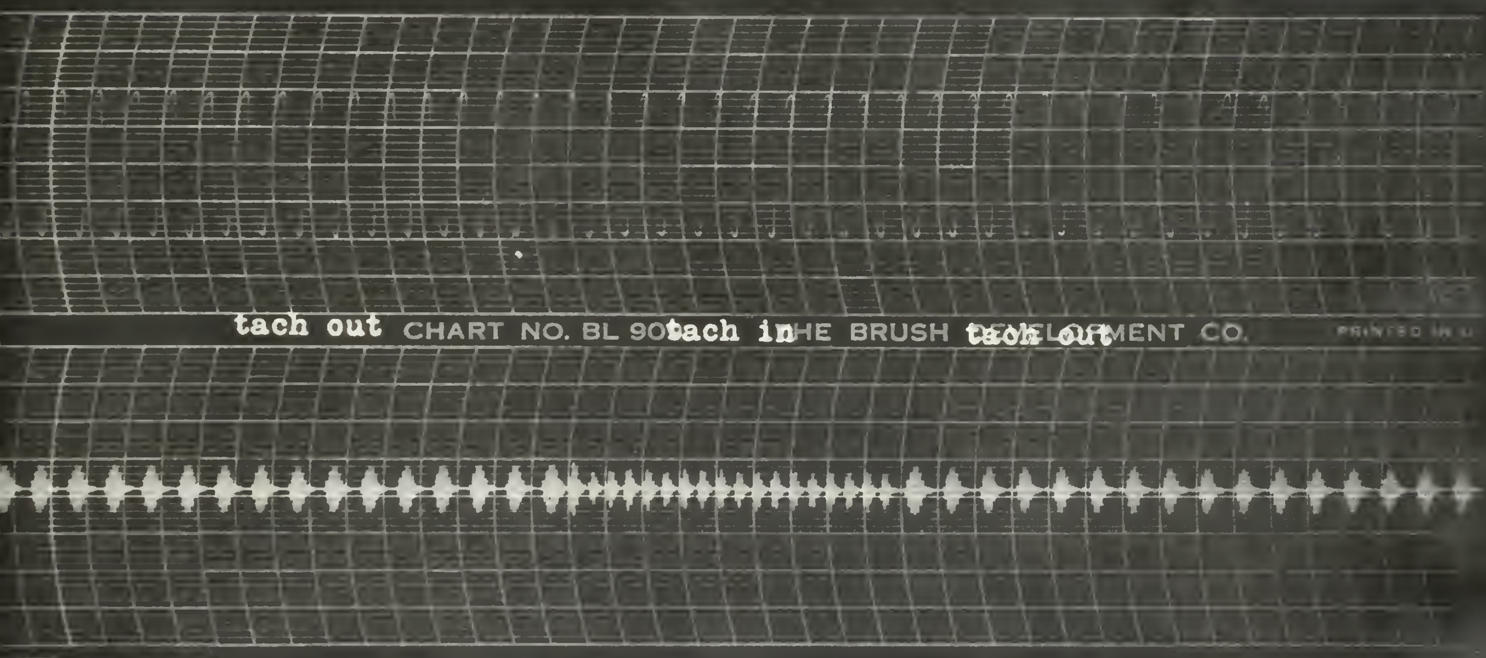
Run G1 5.070 cycles No feedback Minimum bias
Phase shift: 82.1° lag



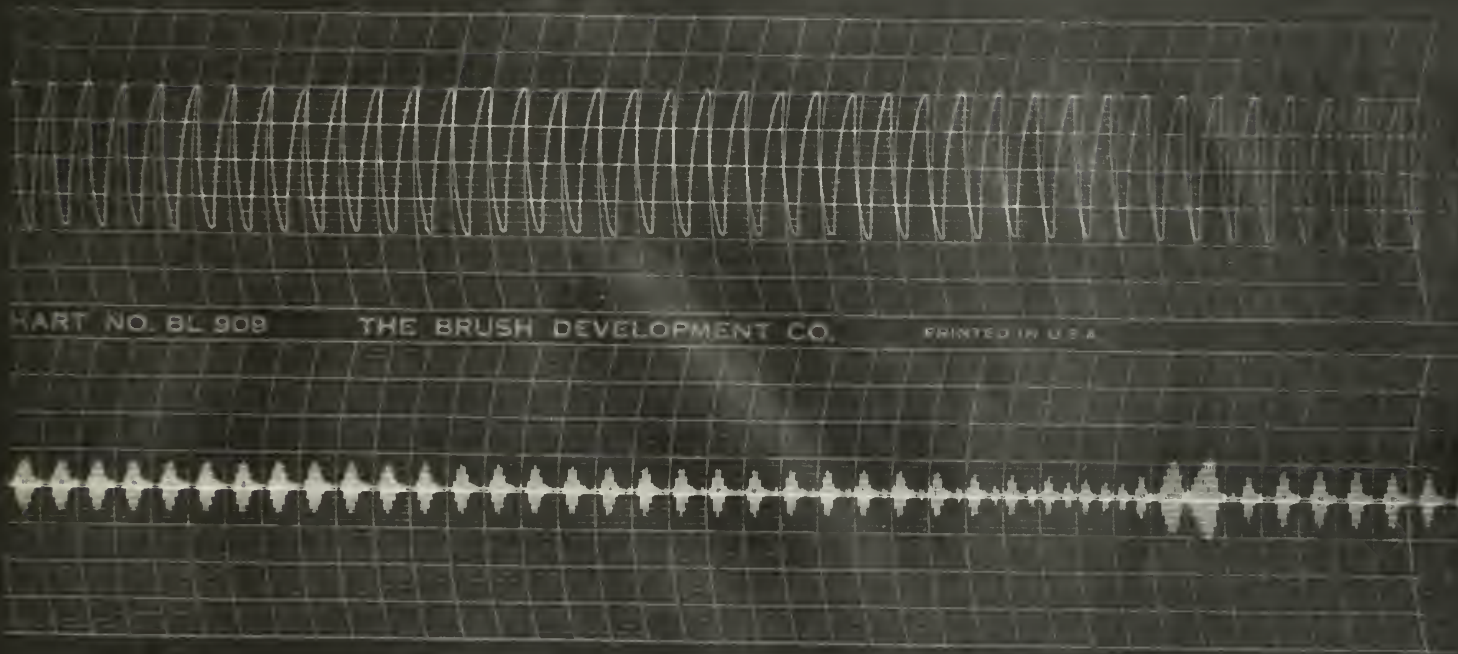
Run G2 5.070 cycles With feedback Minimum bias
Note: Unbalance Phase shift: 75.5° lag



Run G3 5.070 cycles With feedback Minimum bias
Tach circuit in Phase shift: 120.45° lag



Run G4 5.070 cycles With feedback Minimum bias
Tach circuit in & out



Run G5 5.070 cycles With feedback Minimum bias
Tach circuit out
Effect of varying balance to obtain balanced output